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A COMPILATION OF SUBSURFACE
HYDROGEOLOGIC DATA
VOLUME I - MAIN REPORT

by

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Research report

A COMPILATION OF SUBSURFACE
HYDROGEOLOGIC DATA - VOLUME I

ABSTRACT

This report presents a compilation of both fracture properties and hydrogeological parameters relevant to the flow of groundwater in fractured rock systems. Methods of data acquisition as well as the scale of and conditions during the measurement are recorded. Measurements and analytical techniques for each of the parameters under consideration have been reviewed with respect to their methodology, assumptions and accuracy. Both the rock type and geologic setting associated with these measurements have also been recorded.

RÉSUMÉ

Ce rapport présente une compilation des propriétés des fractures et des paramètres hydrogéologiques relatifs au ruissellement des eaux souterraines dans des systèmes de roches fracturées.

Les méthodes d'acquisition des données ainsi que l'échelle de mesure et les conditions dans lesquelles elles ont été faites ont été relevées.

Les mesures et les techniques d'analyse de chacun des paramètres considérés ont été évaluées en fonction de leurs méthodologie, hypothèses et précision.

Le type de roche et la structure géologique relatifs à ces mesures ont également été relevés.

DISCLAIMER

The Atomic Energy Control Board is not responsible for the accuracy of the statements made or opinions expressed in this publication.

(ii)

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1.0 INTRODUCTION

1.1 Scope

One of the major concepts for high level nuclear waste is the disposal of these wastes deep in bedrock. Many of the international nuclear waste isolation programs are considering crystalline rock masses as the candidate rock types. Virtually all of these nuclear waste disposal programs are required to undertake some form of performance assessment. The purpose of this assessment is to evaluate the impact that the construction of such a nuclear waste repository would have on the environment (in general) and on humans in particular. One of the prime mechanisms which would be responsible for the release of radioactive material is the dissolution and leaching of the waste by groundwater. This, coupled with the subsequent movement of the dissolved radionuclides through the groundwater, provides one of the most likely pathways for exposure to humans. To evaluate the risk posed to people via this potential pathway, it is essential that the movement of solute and groundwater in the geologic formations under consideration be understood. To this end, the Atomic Energy Control Board has commissioned this study to identify and review hydrogeologic properties pertinent to the flow of groundwater in the geologic environments being considered by the Atomic Energy of Canada Limited (AECL) waste disposal program.

In Canada, efforts have been concentrated on characterizing plutons. In these rock masses, the flow of groundwater is primarily through zones of fractures as opposed to the intact rock matrix. As such, information pertaining to groundwater flow through fractured rock systems may be relevant to the Canadian disposal program and has been included in this study.

The hydrogeological properties that describe groundwater movement through fractured rock systems are the focus of this review. This study reviews such properties as hydraulic conductivity, storage coefficient and the parameters comprising these quantities as well as parameters describing fracture characteristics. In addition, the variation of these parameters as functions of other independent variables has been explored. The review has examined properties for both the rock matrix and fractures and has recorded pertinent information regarding the measurement of these parameters, such as the scale of the measurement and test method. In addition, commonly used test methods have been described and evaluated with regard to their accuracy and applicability.

1.2 Sites of Interest

In reviewing the available information available describing groundwater flow through fractured rock it became apparent that by far the vast majority of detailed, well documented data that were available in the literature pertained to a relatively small number of research areas. These sites were typically the focal point of research programs being conducted by government laboratories or agencies in support of high level nuclear waste disposal programs. These research sites include:

- Stripa Mine, Sweden;
- Finnsjon, Kamlunge, Fjallveden, Gidea, Svartboberget Sites, Sweden;
- Olkiluoto, Loviisa, Lavia Sites, Finland;
- The Climax Granite Mine Site, Nevada Test Site;
- Office of Crystalline Repository Development (OCRD) room Colorado School of Mines (CSM), Edgar Mine;
- Savannah River Plant at Aiken, South Carolina;

- Oracle site, Oracle Arizona;
- Basalt Waste Isolation Project (BWIP) Hanford, Washington;
- Atomic Energy of Canada Limited's (AECL) Underground Research Laboratory
- AECL's Atikokan Research Area;
- AECL's Chalk River Research Area;
- AECL's Whiteshell Research Area;

Other sources of information have been included where sufficient site specific geologic and hydrogeologic information is provided. This would include information from a number of miscellaneous sites and laboratory investigations such as geothermal sites, university investigations, other nuclear waste isolation programs. In order to facilitate correlations between parameters at specific sites, this report has been organized so that hydrogeologic parameters (factors influencing them and test methods) are presented in separate chapters. Site specific data is presented in accordance with the research area of interest in Chapter 5.

2.0 PERMEABILITY

2.1 Definitions

The flow of fluids through geologic media was first described mathematically by Darcy (1856) while investigating the flow of water through homogeneous sand filters in connection with the city of Dijon, France. Darcy found that the rate of flow (Q) was proportional to both the cross-sectional area (A) and the head (h) difference across the filter and inversely proportional to the length (or thickness) of the filter. Darcy's observation can be expressed mathematically as:

$$Q = KA \frac{dh}{dx} \quad (2-1)$$

where K is a coefficient of proportionality known as the hydraulic conductivity and dh/dx is the hydraulic gradient in the direction of flow. In a homogeneous medium, Darcy's Law may be stated as the specific discharge per unit hydraulic gradient. The hydraulic conductivity is a function of both fluid and media properties. Nutting (1930) expressed this relationship in terms of these properties as:

$$K = \frac{k \rho g}{\mu} \quad (2-2)$$

where ρ is the fluid density, μ the fluid viscosity and g is the acceleration due to gravity. The rock dependent property is described through the variable k and is known as the permeability or intrinsic permeability of the media.

Darcy's (1856) original observations were based on flow in one-dimension. Because of this, Darcy originally defined his coefficient of proportionality as a scalar quantity. In most hydrogeologic regimes, however, flow is not limited to one-dimension. In multi-dimensional flow systems, hydraulic

conductivity, or more specifically permeability, (because fluid properties are non-directional) must be represented by a tensor. A three dimensional extension to Darcy's law can therefore be written in matrix form in terms of a Darcy velocity ($V=Q/A$) as:

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \frac{\rho g}{\mu} \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \begin{bmatrix} \frac{\delta h}{\delta x} \\ \frac{\delta h}{\delta y} \\ \frac{\delta h}{\delta z} \end{bmatrix} \quad (2-3)$$

If the permeability matrix is symmetric, the values can be resolved into their principal components, that is:

$$k_{ij} = \begin{bmatrix} k_{xx} & 0 & 0 \\ 0 & k_{yy} & 0 \\ 0 & 0 & k_{zz} \end{bmatrix} \quad (2-4)$$

Unfortunately few measurements are made to assess the directional values of hydraulic conductivity. Most permeability tests are one-dimensional (e.g. single borehole tests, permeameter tests on cores) and permeability is evaluated as a scalar.

Fractured Rock

Equations (2-1) and (2-2) were originally developed for porous unconsolidated media. If one assumes that flow through fractured rocks approaches that of flow through parallel planar plates, then, for laminar conditions, the discharge (L^3/T) may be described (for a single set of parallel plates) as:

$$Q = \frac{b^3 \rho g}{12 \mu} \frac{dh}{dx} \quad (2-5)$$

where b is the fracture aperture.

By comparison with equation (2-1) the fracture conductivity K_f can be defined as:

$$K_f = \frac{\rho q b^2}{12\mu} \quad (2-6)$$

Unfortunately flow through (actual) naturally occurring fractured rocks does not usually occur in single fractures but rather through fracture zones having frequencies of tens to hundreds of fractures per meter. In addition natural fractures are not smooth but typically possess some degree of roughness. This, together with the existence of fracture infillings and the non parallel nature of the fractures, has resulted in only partial validation for the cubic law (Equation 2-5) as reported by Witherspoon et al. (1981a).

While most of the recent efforts regarding the validation of the cubic law have centered on laboratory studies of a single fracture (Witherspoon et al., 1979a,b; Kranz et al., 1979) some researchers have utilized this approach to calculate the aperture of a single hypothetical fracture (i.e., equivalent single fracture) whose theoretical hydraulic response would match the results of their permeability test (e.g., Davison, 1980). Alternately, some researchers analyze these tests by assuming the entire tested interval is homogeneous and isotropic. This enables an equivalent porous media estimate to be made. The danger associated with both of these approaches is that the value calculated (i.e., either the equivalent single fracture, or equivalent porous media value) may be a function of the length of test interval (e.g., packer spacing). This will be the case if, as in most naturally occurring fractured rock systems, the fracture spacing and aperture size are irregular.

The nature of naturally occurring fracture systems also gives rise to two types of rock permeability, fracture and matrix. As the names imply, matrix permeability refers to the permeability of the intact rock mass, while fracture permeability refers to the higher permeability associated with either distinct fractures or highly fractured zones. Bulk permeabilities typically refer to the overall permeability of the rock mass combining matrix and fracture permeabilities. The nature of the test being employed to measure permeability together with the state of the rock mass will determine if the quantity being measured is fracture or matrix or (if bulk) what percentage is likely to be matrix versus fracture. Pressure pulse and permeameter measurements performed on cores will typically yield matrix permeability values. Relatively short term field tests conducted in highly fractured rock will most likely yield estimates of fracture permeabilities. These and other tests used in obtaining permeability estimates are described in more detail in Section 2.4.

2.2 Influencing Factors

2.2.1 Temperature

Temperature can influence the hydraulic conductivity of a medium in a variety of ways. Hydraulic conductivity is dependent on fluid properties (such as density and viscosity which are functions of temperature) as well as those of the porous medium. For water, viscosity changes may be significant over relatively small temperature changes, but the magnitude of density variations for the range of temperatures likely to be encountered in most environments (even in the vicinity of a high level nuclear waste repository) is substantially less. Variations due to changes in fluid properties may be removed if one considers solely the permeability of the medium. However, even for this case, the existence of a number of mechanisms

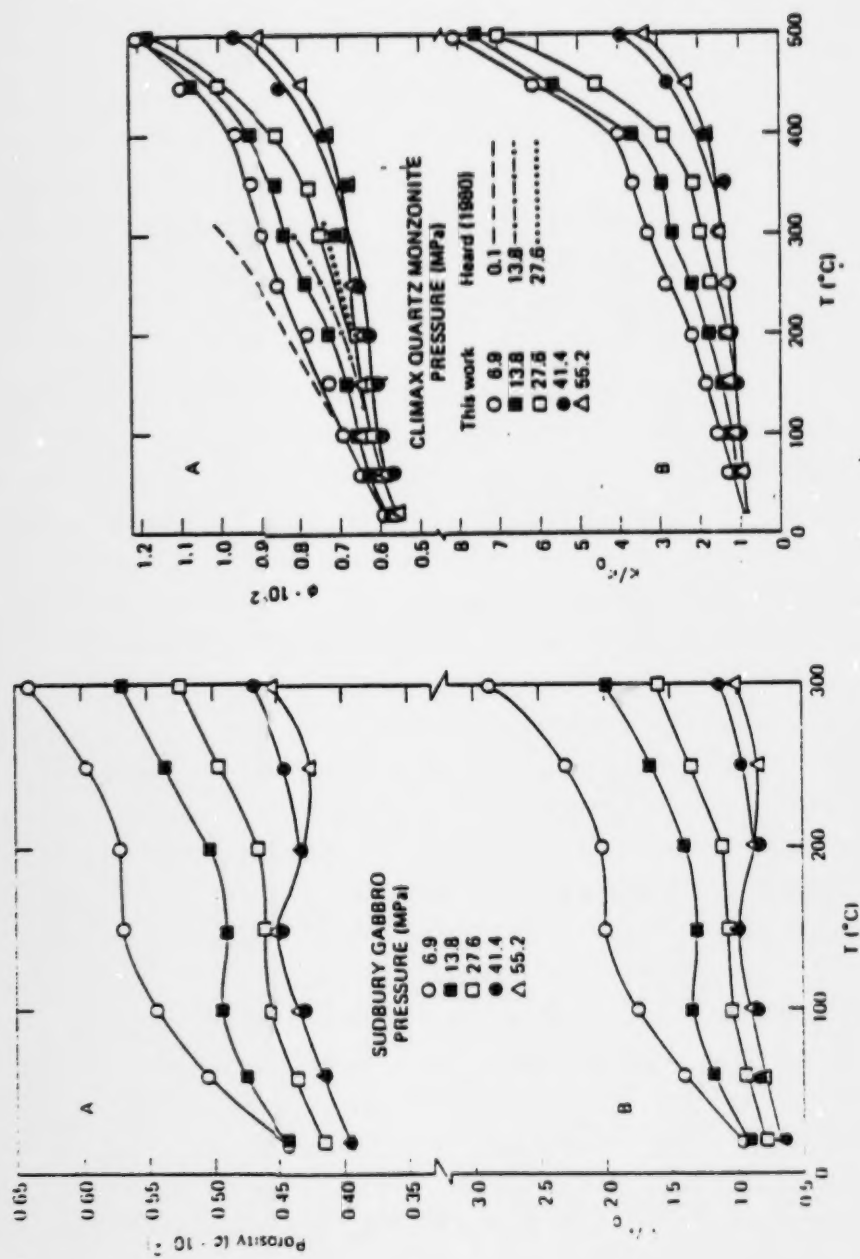
complicates the observed relationship between permeability and temperature. These mechanisms have been identified by a number of researchers and include dissolution and precipitation of minerals, fracture closure due to thermal expansion and thermally induced cracking.

Studies conducted by Summers et al. (1978) and Morrow et al. (1981) both found that the dissolution and subsequent precipitation of quartz and other minerals was instrumental in reducing the fracture permeability in tests conducted at elevated temperatures on granitic samples. The work conducted by Summers et al. (1978) indicated an initial increase in permeability which was 1 to 2 orders of magnitude greater than the room temperature permeability. The initial increase was attributed to thermal stress cracking. Subsequently the dissolution of quartz and plagioclase near the inlet and deposition of these minerals through the sample (due to oversaturation) caused a substantial reduction in permeability. This effect was most noticeable at high temperatures. The study conducted by Summers et al. (1978) consisted only of measuring permeability at elevated temperatures. Permeability measurements were not made upon "cooled" samples.

These findings are very similar to those of Morrow et al. (1981) and Potter (1978). The study conducted by Potter (1978) examined temperature effects for both Westerly granite and Los Alamos granodiorite. The granodiorite experienced an order of magnitude decrease in permeability for a temperature increase to 200°C. Permeability recovered to pre-test values upon cooling. The Westerly granite experienced the same processes (thermal cracking and water-rock chemical reactions) observed by Summers et al. (1981). In this case, however, thermal cracking was found to be the dominant mechanism causing a permanent increase in the permeability of the sample.

The study undertaken by Morrow et al. (1981) found mineral deposition to be the dominant mechanism affecting permeability. This deposition was attributed to decreasing solubility along the temperature gradient and resulted in a 1 to 2 order of magnitude reduction in permeability. This reduction was, as found by Summers et al. (1978), a function of the temperature. At a temperature of 200°C this reduction occurred over a one month period, while at 310°C the permeability was reduced by a factor of 20 in just a few days.

Another study conducted by Page and Heard (1981) examined the variation of elastic moduli and thermal expansion with temperature for Sudbury gabbro and quartz monzonite from the Climax Stock at the Nevada Test Site. By calculating the difference between observed thermal expansivity to a theoretically calculated value (based on mineral composition for an intact sample) a relationship for the change in porosity as a function of temperature was derived. By assuming permeability is proportional to the cube of porosity, Page and Heard (1981) derived a similar relationship for permeability. It should be stressed that both of these relationships are based on theory which is not wholly substantiated and therefore the resulting curves should be used with caution. However, in spite of this fact the resulting curves indicate interesting trends which support some of the findings of the researchers described previously. For example, the gabbro samples exhibited an increase in porosity (associated with the thermal expansion of the grains) during early time followed by a decrease in the rate of porosity increase (sometimes to the point of being a net porosity decrease) due to expansion of mineral components in existing cracks. Subsequently the porosity increased due to induced thermal cracking. Figure 2.1 represents the inferred porosity behavior for both the Sudbury gabbro and Climax quartz monzonite (after Page and Heard, 1981).



Voegele et al. (1981) conducted a large scale in situ coupled thermo-mechanical-hydraulic test on a 2 m by 2 m by 2 m gneissic block located in the Colorado School of Mines (CSM) experimental mine in Idaho Springs. The results of these tests are discussed in more detail in Section 2.2.2 (pressure effects) and only the temperature dependent effects are discussed here. Temperature was found to have a significant impact on fracture permeability. A temperature increase from ambient temperature (12°C) to 73.6°C resulted in over an order of magnitude decrease in permeability from 75 darcys ($7.4 \times 10^{-11} \text{ m}^2$) to 6.8 darcys ($6.7 \times 10^{-12} \text{ m}^2$).

Voegele et al. (1981) point out that such a reduction in the flow aperture could only be achieved at ambient temperature with exceptionally high stress levels and attributes the permeability reduction to improved mating of opposite fracture walls. This improved mating of the asperities could be maintained at ambient temperature if a normal stress of sufficient magnitude (in this case 3.45 MPa) were applied. Figure 2.2 summarizes the aperture, temperature and stress relationships determined from the CSM heated block test.

Other large scale tests include the in situ tests conducted in the Stripa granite (Lundstrom and Stille, 1978). The permeability of the rock was observed to undergo a factor of four reduction when experiencing a temperature rise from 10°C to 36°C.

In summary, therefore, it can be said that a number of phenomena may result from subjecting crystalline rocks to higher temperature. They include:

- aperture closure due to thermal expansion of the mineral constituents;
- thermally induced stress cracking; and
- dissolution and subsequent deposition of minerals.

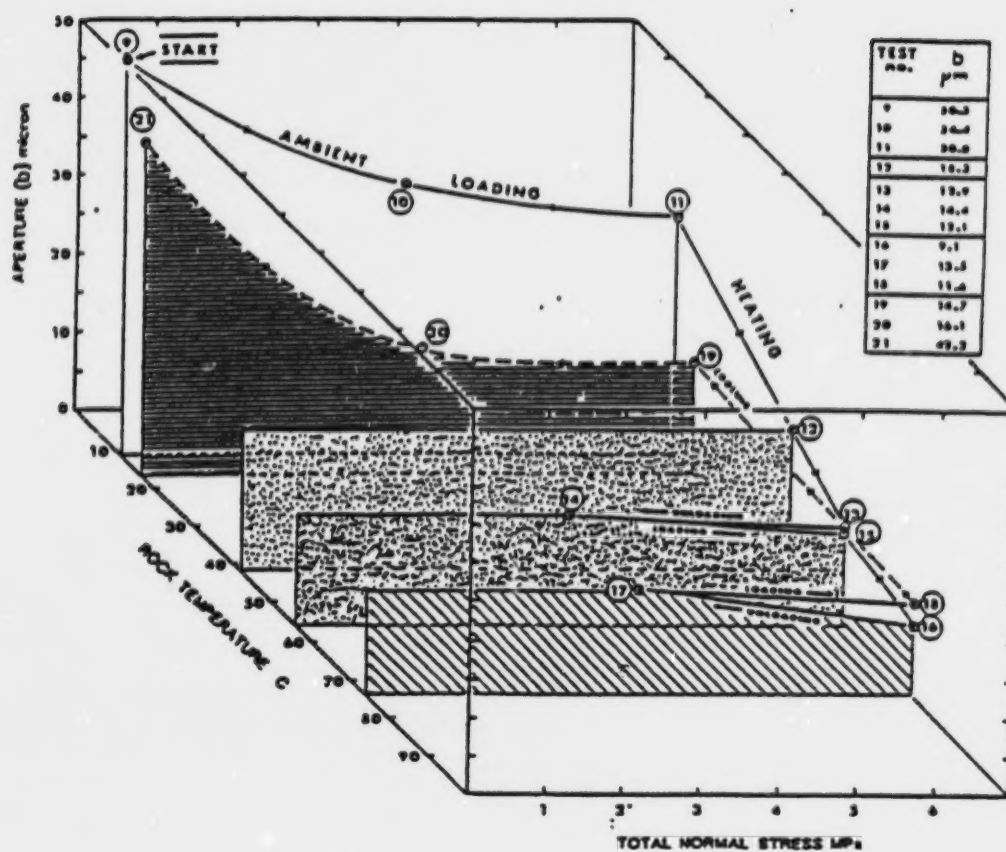


Figure 2.2 Aperture as a function of Stress and Temperature (after Voegele et al., 1981)

Most of these mechanisms (the exception being thermal cracking) tend to decrease the permeability of the rock mass. Although these mechanisms may result in large changes to the permeability of the media, the magnitude of these changes is difficult to quantify.

2.2.2 Pressure/Stress

Numerous investigators (e.g. Witherspoon et al., 1979a,b; Gale et al., 1979a,b; Kranz et al., 1979; Gale and Raven, 1980; Iwai, 1976; and Pratt et al., 1977) have investigated the fracture permeability as a function of stress at ambient temperature conditions. The majority of these studies examined changes in aperture, flow rate or fracture permeability when a uniaxial load was applied normal to the fracture plane. In virtually all of these cases permeability decreased with increasing stress. Voegele et al. (1981) presented a figure (reproduced in Figure 2.3) which summarises the findings of many of these researchers as well as the results of his heated flow tests conducted in a gneissic block in Colorado School of Mines facility at Idaho Springs. It can be seen that a general decrease in permeability with increasing stress exists. The decrease would also appear to be proportional to the temperature of the test. Similar curves have been obtained by Kranz et al. (1979), Gale and Raven (1980) and Voegele et al. (1981) and have been reproduced in Figures 2.4(a) and (b), and 2.5 respectively. One feature that is apparent from these figures is the apparent hysteretic behavior of the samples. That is a single stress level did not give a unique value for the joint or fracture permeability, but rather depended on the loading history of the sample. This behavior has been observed during both loading and unloading of a specific sample as well as successive loading cycles. Gale and Raven (1980) reported this phenomenon and noted that the magnitude of this effect decreases with successive loading cycles. Gale et al. (1979a

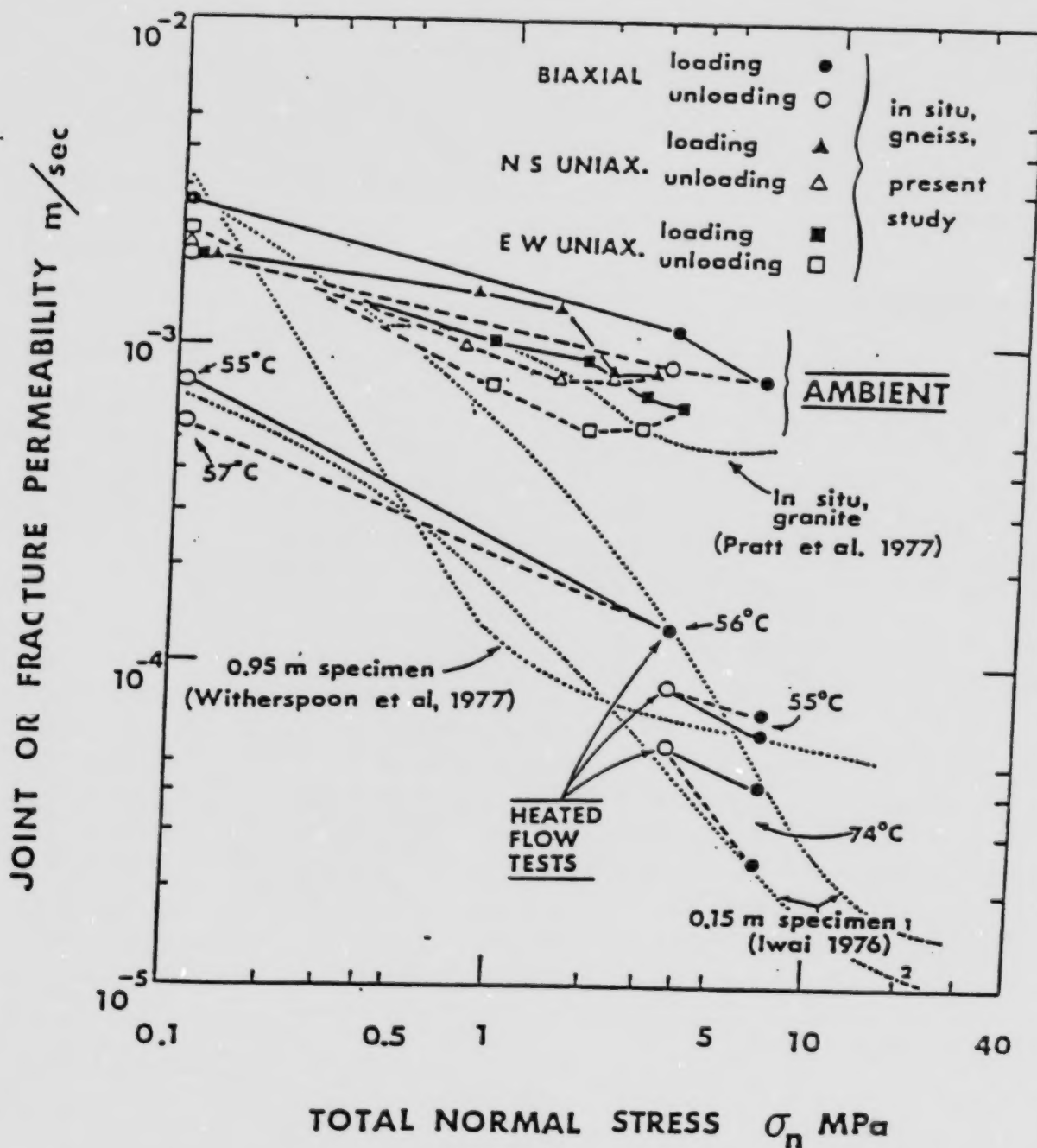


Figure 2.3

Fracture Permeability versus Normal Stress for various Research Studies (Voegele et al., 1981)

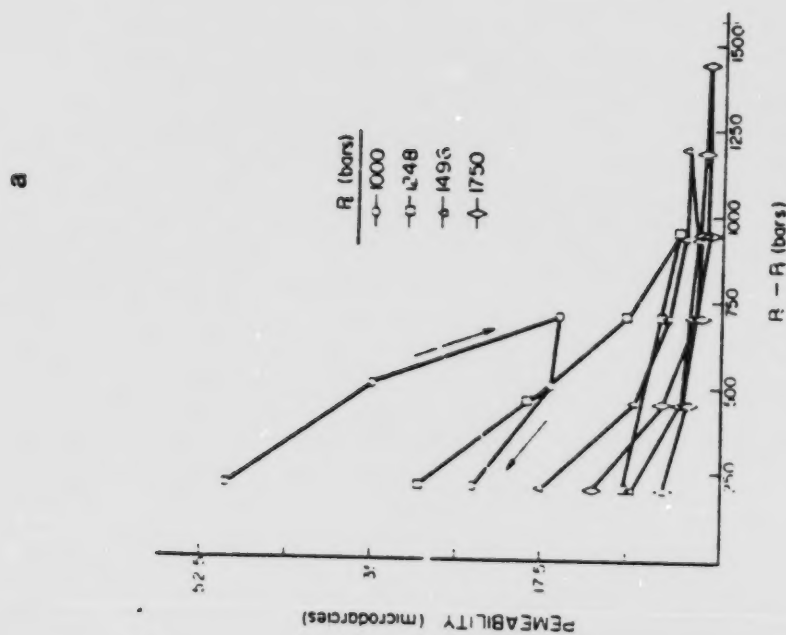
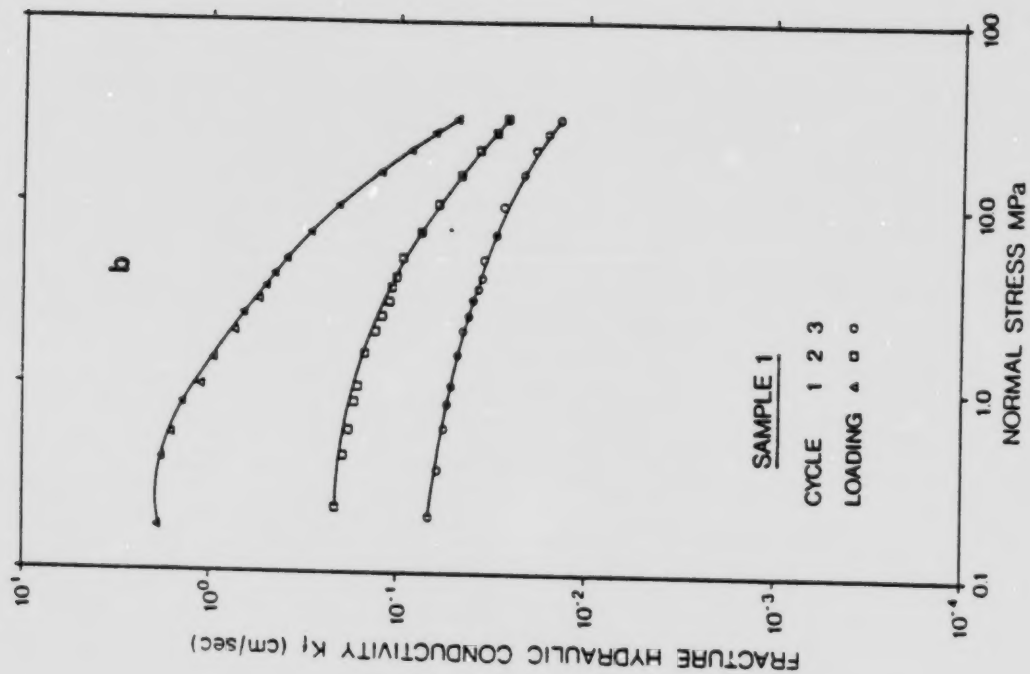


Figure 2.4 Typical stress permeability relationships for axial load conditions after: (a) Kranz et al. (1979) (b) Raven and Gale (1980)

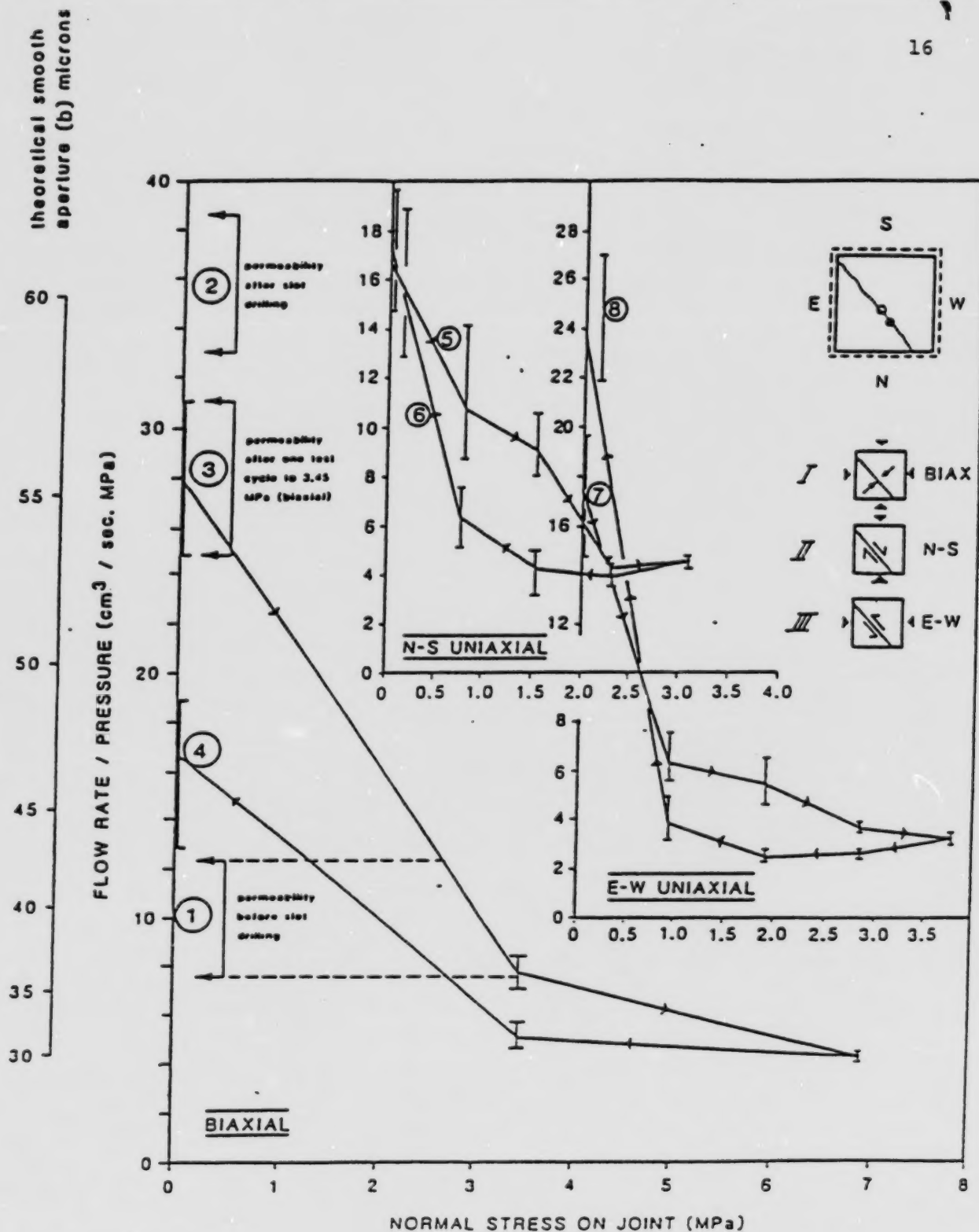


Figure 2.5 Flow Rate versus Normal Stress for Loading/Unloading Cycles (Voegele et al., 1981)

and 1979b) reported similar findings for flowrate experiments performed on both natural and tension induced fractures in Chalk River cores. It is most likely that these observations are due to both crushing of the fracture plane asperities as well as improved seating of the fracture. In virtually all cases, fracture permeability (or flowrate or aperture) decreased with both successive loading cycles and the unloading portion of the test cycle. The results of many of these laboratory investigations (including Gale and Raven, 1980) have been included in Appendix A.

The validity of the cubic law (relating flowrate and aperture size for flat plates) for natural fractures is the subject of some controversy. Some authors (e.g., Witherspoon et al., 1979a,b) have concluded that the cubic law holds for all fractured rock types regardless of stress history or whether fractures were held open or closed under stress. Other researchers (e.g., Kranz et al., 1979) concluded that the flat plate model is inadequate and deviations may occur at high stress levels or for very rough surfaces. Voegele et al. (1981) also concluded that measured changes in fracture aperture (ΔE) with calculated changes in the smooth wall (parallel plate) aperture (Δe) indicates that $E/e > 1$ for rough fractures subject to closure by stress. They attributed their observations to a combination of tortuosity and roughness effects and suggested that the Witherspoon et al. (1979a,b) findings may have been biased by the mathematical technique used to estimate apertures. Gale and Raven (1980) also suggested that deformable natural fractures may deviate from the cubic relationship especially for low flowrates and small apertures when the fracture is subjected to high normal stress conditions. Certainly the existence of infilling materials and the nature of naturally occurring fractures (e.g., uneven walls and variable aperture) have lead other researchers to propose alternate models. For example, Neuzil and Tracey (1981) have developed a model wherein the fracture is represented by a distribution of parallel plate apertures. It is uncertain,

however, whether sufficient data could be collected to characterize the fracture network on a large scale using such approaches.

Trimmer et al. (1980) performed a number of laboratory experiments on intact and fractured samples of Westerly granite, White Lake gneissic granite and Creighton gabbro. In this series of experiments both the effective stress and deviatoric stress (applied parallel to the fracture plane) were varied. The intact gneissic granite had a permeability of 10^{-22} to 10^{-24} m² that was unaltered by changes in either effective or deviatoric stress. The permeability of both the gabbro and the granite did decrease with increasing stress although Trimmer et al. (1980) indicated that large errors in their permeability determinations mask any relationship between permeability and either confining pressure or applied load.

Only a relatively few studies have examined the relationship between in situ stress and permeability. Of these the most notable are the studies of Carlsson and Olsson (1979) and Montazer and Hustrulid (1983). Carlsson and Olsson (1979) conducted a hydrogeologic study in an underground power plant in northern Sweden at Juktan. Hydraulic conductivity was determined (technique not specified) as was the in situ stress of the rock mass. This latter set of measurements indicated the the highest horizontal compressive stress is of the order of 15 MPa with the lowest values being of the order of 3.5 MPa. Vertical stresses corresponded to the approximate weight of the overburden (6.5 MPa). They observed that joints paralleling the direction of the greatest compressive stress were more open relative to joints normal to this direction. They also compared the stress distribution with the hydraulic anisotropy and concluded that hydraulic properties "seem" to be stress dependent.

Montazer and Hustrulid (1983) compared the permeability distribution around the OCRD Room in the CSM mine with the results of stress measurements. They suggested that the lower permeabilities observed in one of the boreholes adjacent to the room are attributable to the orientation of the major principle stress (i.e., permeability may have decreased in a direction normal to the maximum principle stress). Permeability measurements in several boreholes would tend to refute this hypothesis however, and several explanations for these "discrepancies" are proposed.

A third study conducted by Haimson and Doe (1983) examined both the permeability and stress distribution in a deep borehole in northern Illinois. However other than a general observation that permeability values display a general decrease with depth, no conclusions were drawn regarding permeability-stress relationships.

The subject of permeability decrease with depth has been the object of some controversy in the scientific literature. Compilations of permeability values (e.g., Davis and Turk, 1964; Snow, 1968a) corresponding to shallow (less than 50 feet, (15.24 m)) depths show a general decrease in permeability with depth. This observation has prompted a number of researchers to develop permeability versus depth relationships (e.g., Carlsson and Olsson, 1977b; Burgess, 1977). Such relationships typically take the form of an exponential decrease with depth. Although there are many possible explanations as to why such a relationship should (or does) exist, e.g., closure of fractures due to stress, less fracturing and more infilling at increased depths, these general tendencies are typically masked by the highly heterogeneous nature of fracture systems. That is the existence of highly fractured zones will tend to dominate the groundwater flow system. The assumption of a permeability decrease with depth must be considered as an oversimplification since zones of high permeability have been located at large depths (100's to 1000's m) in virtually all deep borehole testing programs.

2.3 Scale Considerations

It is usually assumed that the monitoring system is measuring a representative elementary volume (REV) of the hydrogeologic regime. A REV may be conceptualized as the smallest volume of porous or fractured medium for which the measured values of hydrogeologic parameters or processes are representative. It then becomes necessary to ensure that the sampled volume is representative of the medium of interest. In porous media the REV could depend on the degree of interconnection between pore spaces, which depends on such properties as grain size, compaction, lithification or secondary mineralization. In a fractured medium the REV could depend on the fracture frequency, fracture set orientation, fracture length or continuity. The size of the REV is then dependent on the nature of the medium and is specific to the individual parameter.

In the case at hand, the measurement of hydraulic conductivity can be greatly influenced by the scale of measurement. It then becomes necessary to choose a measurement scale that is either representative of the rock mass including the fractures or a scale that is specific to individual fractures and blocks of intact rock. For example, a long test interval may include one or several fractures separated by intact rock. Hydraulic tests on this interval may be representative of the rock mass as a whole even though shorter, specific intervals containing fractures may have hydraulic conductivities that are dramatically different. Where shorter intervals are used the results are more likely to be representative of specific fractures (if fractures were present in the intervals). Comparisons between intervals of greatly different lengths (i.e., long versus short test intervals) may result in confusion when representative values of the rock mass are required.

The measurement scale also has a significant effect on the appropriate analytical technique that is required for analysis of the hydraulic tests. If large blocks of the crystalline rock are tested such that representative values of hydraulic conductivity, porosity and compressibility can be defined, porous media approximations can be used in the analyses. If smaller intervals are tested then the flow in individual fractures will dominate and the appropriate method of analysis may, in some cases, be a fracture flow model.

For test intervals indicating low to intermediate hydraulic conductivity, additional testing could be conducted using a variety of packer spacings and testing depths to derive a more detailed evaluation of the nature of the hydraulic conductivity (i.e., homogeneous zones, discrete fractures, matrix flow only, etc.). However, it must be emphasized that the implementation of such a detailed testing program to provide this information could substantially increase the efforts and costs of the hydraulic testing program.

The length of the test interval compared to the portion (or portions) of the test interval that dominate the head or pressure dissipation during a hydraulic test is an important consideration. Ideally, from a flow conceptualization and analysis point of view, the full test interval should be contributing. However, it is generally not possible to ascertain the most important portions of the test interval and their contributions to the total permeability. As a result, the full test interval length is usually chosen when interpreting the transmissivity and subsequently the hydraulic conductivity of the tested interval. The hydraulic conductivity is calculated as the transmissivity divided by the formation thickness (i.e., portion of test interval contributing to the most significant proportion

of the pressure dissipation during the test) within the test interval. The formation thickness is usually assumed as the test interval length. In cases where the formation zone is, for example, a factor of 10 smaller than the test interval length, the interpreted hydraulic conductivity would also be in error by a factor of 10. The net effect of averaging over the full test interval length is to overestimate and underestimate the hydraulic conductivity in the lower and higher hydraulic conductivity portions, respectively, of the tested interval. This observation illustrates the need to identify the test interval lengths in order to allow a more representative comparison to other hydraulic conductivity evaluations.

Due to the relatively long time frames being considered in most geologic radioactive waste disposal programs, permeability values tend to be measured at a much smaller scale and extrapolated to the larger regional scale of interest. Brace et al. (1982) pointed out that the actual regional permeability value could be either larger or smaller than that evaluated on a smaller scale. If one were to consider borehole permeability values it can be seen how this might be true. If the borehole did not intersect highly permeable fracture zones then the permeability estimate would approach matrix permeability values. This value would tend to significantly underestimate the hydraulic conductivity of the fracture networks that may exist on a larger scale. On the other hand, a highly conductive fracture zone may not be extensive enough to dominate the groundwater flow system on a regional scale.

There is some laboratory evidence to support the existence of a scale effect for permeability. The curves presented in Figure 2.3 (based on work by Iwai, 1976; Pratt et al., 1977; Witherspoon et al., 1977) led Witherspoon et al., (1979b) to suggest the existence of a possible scale effect on fracture permeability. They observed that the minimum value of fracture hydraulic (associated with the highest stress levels) increased with sample size. The heated block test conducted by Voegele et al.

(1981) would tend to support this hypothesis although the latter points to differences in fracture type (i.e., naturally occurring versus experimentally induced) and the behavior differences associated with these fracture types. Gale and Raven (1980) tested five granite cores of varying diameter and indicated that the results of their study suggested that a sample size effect exists. Their results contradicted the findings of Witherspoon et al. (1979b) in that the smallest samples had the highest hydraulic conductivities at maximum stress. They attributed their observations to the fact that large samples have a larger initial distribution of contact points enabling them to deform more elastically.

2.4 Test Methods

2.4.1 In Situ Test Methods

The in situ hydraulic conductivity of a geologic media is typically evaluated through the use of boreholes drilled into the formation of interest and involves using various pieces of equipment to isolate specific test zones. The two main groups of isolation devices are piezometers and packer systems.

Piezometers may be regarded as permanent because they act to isolate a selected interval that does not change with time. Piezometers may be constructed in several configurations including a single piezometer, multiple piezometer (several piezometers in one borehole), piezometer nest (a group of single piezometers completed at different elevations), or multiple port piezometers (ports along the casing can be open and closed to access selected intervals).

Packer systems consist of an arrangement of packers (inflatable flexible glands) which, when inflated, isolate a selected zone in the borehole. Hydraulic testing is usually carried out in an interval in the open borehole which is isolated by one or more packers. Packer systems may be moved

along the length of the borehole so as to test different intervals of the formation. Test interval length may also be varied. Pressure and often temperature are monitored in the test interval using pressure transducers and thermistors.

Three configurations of packer systems exist, including single, straddle and guarded-straddle packers. Single packers are used during drilling to test the zone below the drill string between the bottom of the hole and the packer. Straddle packers consist of two packers at adjustable spacings which are used to conduct hydraulic testing in selected zones throughout the borehole. Problems associated with single and straddle-packer configurations include leakage at the packer seal with the borehole wall (packer leakage) or hydraulic communication through the formation (packer bypass). As a result, guarded straddle-packers were developed. This configuration consists of four packers in which the inner two isolate the test zone while the outer two isolate zones monitored to detect leakage.

In situ tests can be broadly classified as either single or multiple borehole tests. Each of these categories provide hydraulic conductivity estimates that are representative of different scales. Single borehole tests are usually limited to testing the region in the immediate vicinity of the borehole. Multiple borehole tests, on the other hand, provide permeability estimates over potentially much larger distances - equal to the borehole spacing. Both categories rely on introducing a perturbation to the hydrogeologic system. Multiple borehole tests use essentially the same techniques as single borehole tests. Hydraulic testing techniques are usually further classified on the basis of the perturbation technique, e.g., slug test, pulse test, pump test, injection test, etc. The individual methods are discussed in detail in the following sections.

2.4.1.1 Single Borehole

(i) Slug Test

A slug test is defined as an "instantaneous change in water pressure of a test interval by injection or withdrawal of a known volume of fluid, swabbing with the drill stem, or by introducing a solid slug of known volume" (Earth Technology Corp., 1985b). The pressure or hydraulic head is monitored as the perturbation recovers to its original value. Slug tests are a transient test and the recovery versus time relationship is characterized by an exponential function. In a slug test water must actually flow in or out of the test interval before a head/pressure change is registered. Slug tests are most applicable to hydraulic testing in rock masses with a hydraulic conductivity between 10^{-9} and 10^{-4} m/s (Wilson et al., 1979) as shown in Figure 2.6 but may also be used in lower permeability media. This range of hydraulic conductivities has been confirmed in the Canadian Nuclear Waste Disposal Program as reported in Raven (1980). In low hydraulic conductivity rock a long period of time is generally required for recovery. Head measurements are further complicated by barometric and temperature variations. The difficulties in slug test application may be reduced to some extent by using a narrow diameter borehole (Bredehoeft and Papadopulus, 1980); however, physical limitations on the size of monitoring equipment set the lower limit for borehole diameter.

In creating the hydraulic perturbation, it is necessary to consider the magnitude of the perturbation relative to the sensitivity of the monitoring equipment. For slug testing, it is desirable to monitor recovery until approximately 70% of the initial perturbation has dissipated in order to

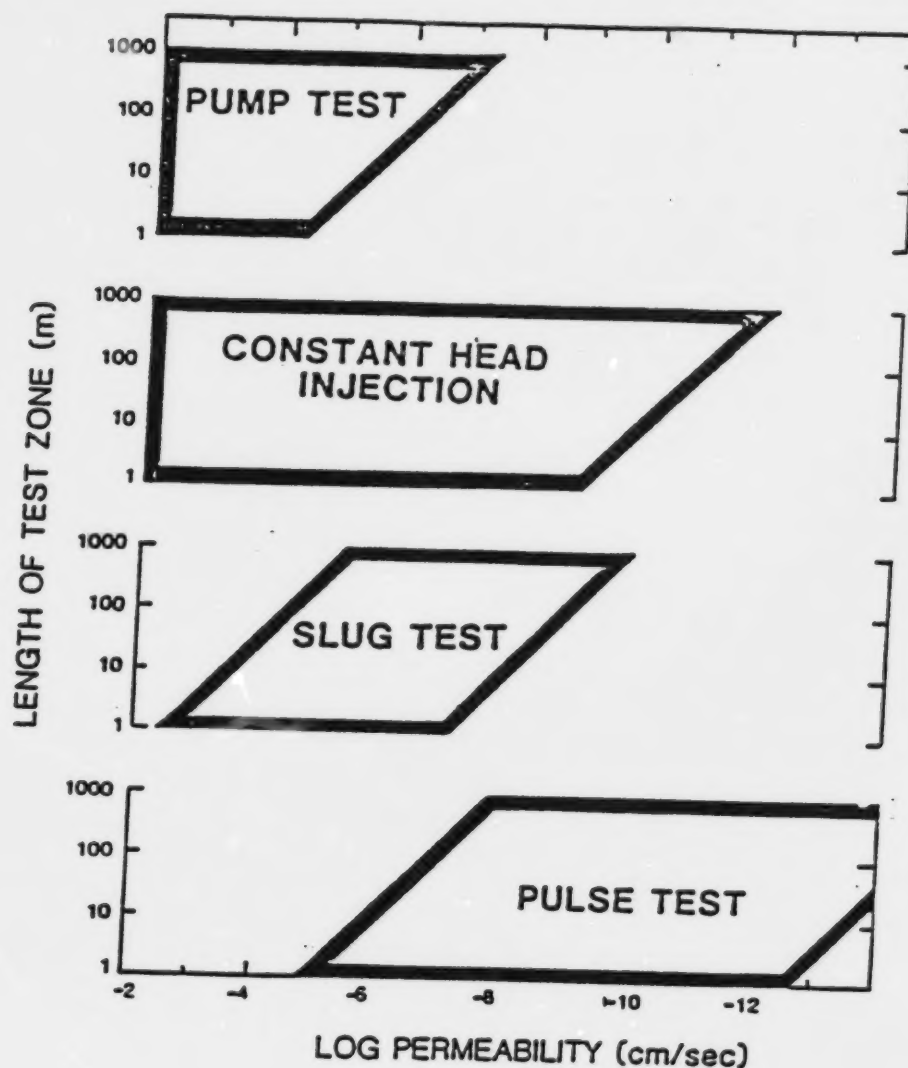


Figure 2.6: Guide to Selection of Well test techniques for permeability measurements. Limits are sensitive to equipment, well geometry and test time (after Wilson et al., 1979)

accurately match theoretical and observed data. Thus, the initial perturbation should be adequate to ensure that pressure readings can be measured reliably given the limitations on monitoring equipment. However, the initial pressure change should be less than the least principal rock stress to ensure that deformations of the rock mass are small compared to aquifer storage effects (Bredehoeft and Papadopoulos, 1980). Unfortunately, this value of rock stress is usually unknown. Slug tests should be conducted using an initial pressure change just adequate to allow recovery to be monitored. Typical initial pressure perturbations vary from one to ten meters of water (Bredehoeft and Papadopoulos, 1980).

Slug tests may be analyzed using a variety of techniques ranging from analytical solutions to numerical models. Cooper et al. (1967) developed an exact solution to the radial groundwater flow equation for saturated porous media. Inherent in his solution are a number of assumptions including a fully penetrating well screen completed over a homogeneous isotropic aquifer of uniform thickness. In porous media, permeability estimates are generally obtained by matching observed data to a series of type curves. The value of permeability obtained using this technique is generally fairly reliable although the storage coefficient may be subject to considerable uncertainty. This technique has been applied to fractured rock systems yielding a porous media equivalent estimate of the permeability. The danger of this approach is obtaining a single horizontal permeability estimate that may be a function of the test interval length (i.e., irrespective of fracture distributions).

Using the "parallel plate" theory the equivalent porous media permeability obtained from the Cooper et al. (1967) analysis approach may be converted into an equivalent single fracture

aperture. Other researchers have developed analytical solutions which are more specific to slug tests in fractured rock systems. In particular, Barker and Black (1983) developed a solution for a fully penetrating well in a fractured rock system which includes the interaction of fluid between the rock matrix and fracture. The solution is subject to a number of typical "parallel plate" assumptions regarding the spacing, orientation and aperture of the fracture system. Barker and Black (1983) suggest that their solution be used to evaluate errors which may be introduced through standard type curve analysis. They state that transmissivities obtained using the latter method will underestimate the actual by a factor not exceeding three and could underestimate the storage coefficient by up to a factor of 10^6 . The Barker and Black solution, along with that of Cooper et al. (1967) are presented in more detail in Section 2.4.3.

Slug tests are, as most hydraulic tests, subject to a number of factors that may influence the ability of the test to obtain a representative hydraulic conductivity estimate. This includes such factors as skin effects, accuracy of equipment readings and depth measurements and compliance of the test equipment. Additional factors that should be considered include the extent of the radius of influence and the appropriateness of assumptions which may be inherent in the analysis technique. These factors are discussed in detail in Section 2.4.3 for both slug and other test methods.

(ii) Pressure-Pulse Tests

Pressure-pulse, pulse or piston tests induce a perturbation similar comparable to the effect of a slug injection/withdrawal test, the difference being that the

perturbation is created by causing a pressure change in the test interval by pressurising a finite volume of fluid rather than actually removing the fluid. Pressure response is governed by compressibility effects with very little flow of fluid occurring. The duration of the test may be much shorter than other tests since this test relies on pressure (as opposed to fluid volume) dissipations. This is more desirable in low permeability or tight fractures where flow to and from the test section occurs at very slow rates.

The pressure-pulse test is applicable over a range of hydraulic conductivities from approximately 10^{-15} to 10^{-7} m/s (Wilson et al., 1979) (Figure 2.6); however, Raven (1980) reported that the test is generally suited to formations with hydraulic conductivities in the low to intermediate range (i.e., 10^{-13} to 10^{-9} m/s).

Pressure-pulse tests require highly sophisticated and accurate downhole monitoring equipment consisting of packers, pressure transducers and thermistors and as a result are much more susceptible to equipment related problems than are other hydraulic testing techniques. Typical problems include erroneous results due to packer compliance (elasticity), air leakage from the pulse piston and thermal expansion and contraction effects generated by thermal gradients. These considerations are discussed in detail in Section 2.4.3.

In situ pressure pulse testing in fractured formations may be analysed by a variety of techniques such as numerical models and analytical solutions to simplified representations of the physical system. For example, Wang et al. (1977) developed an analytical expression for evaluating pulse tests for a single tight fracture intersecting the wellbore using solely

the non-continuum approach. The solution assumes an impermeable rock mass and with water flow through the fracture. In their work, aperture size is assumed to remain constant over the duration of the test. This is a reasonable assumption when the applied pressure pulse is much less than the in situ pressure. For single fractures, a relationship was developed between the time to achieve a given pressure recovery and the effective aperture size. For multiple fractures, an effective aperture size can be deduced but the distinct number of fractures cannot be accurately obtained due to the similarity in pressure response type curve shapes. For tilted fractures, the area of contact of the fracture with the wellbore is increased and is elliptical in shape. As a result, the aperture size is likely overestimated. This can be corrected if the fracture tilt or inclination is determined through other means (e.g., borehole televiewer).

The effects of finite fracture extent and changes in aperture on the pressure response are deducible and are discussed by Wang et al. (1977) in a cause and effect approach.

(iii) Injection Tests

Injection tests consist of injecting fluid to a specific interval which is usually isolated using packers. In most applications, only the steady state portion of the test is analyzed, although it is possible to analyze the transient portion. Injection tests may be classified as either constant head or constant flow tests.

Constant head tests are most common and involve injecting fluid under a constant head while monitoring the flow rate until it stabilizes at a steady state value. The test

methodology involves achieving steady state for several different values of constant head. The constant head test is also known as the Lugeon test, the packer test, constant-pressure fluid injection test, water loss test and water pressure test.

The constant flow test involves maintaining a constant injection rate while monitoring the changes in pressure in the test interval until the pressure measurement stabilizes at a relatively constant value.

Steady-state will theoretically never occur; however, it will appear to occur when the single fracture or fracture network is leaky or intersects a fracture of much higher hydraulic conductivity. In finite fractures, the flow rate will reduce with time until governed by the permeability of the rock matrix.

Injection tests are applicable over a wide range of hydraulic conductivities from 10^{-12} to 10^{-4} m/s (Wilson et al., 1979) (Figure 2.6) with the primary lower limit of measurement related to the inability to measure very small flow rates. In the Stripa program in Sweden, flow rates as low as $0.05 \text{ cm}^3/\text{min}$ have been measured (using bubble flow meters) which led to determination of hydraulic conductivities of 10^{-12} m/s for a 10 m interval (Wilson et al., 1979). The lower limit in aperture measurement is one micron using the bubble flow meter technique.

Heish et al. (1983) compare injection tests to those of pressure-pulse tests and found that comparable values were obtained for hydraulic conductivities between 10^{-12} to 10^{-9} m/s. The constant rate test led to slightly

higher values when testing formations at the lower end of the hydraulic conductivity range possibly due to the larger rock mass sampled by the injection test over the pulse test.

While the steady-state assumption facilitates the calculation of a hydraulic conductivity, care must be exercised both in conducting the test (e.g., to ensure steady-state has been reached) as well as the subsequent analysis. Doe and Remer (1980) examined the porous media solution of Hantush to illustrate the errors that may occur using a steady-state approach. They found that the steady-state assumption leads to an overestimation of hydraulic conductivity by less than an order of magnitude for the most extreme cases and is generally within a factor of two to three of the value obtained from a transient analyses. One difficulty with this (steady-state) solution is knowing the correct radius of influence to employ. However, the hydraulic conductivity is relatively insensitive to fairly large changes in radius of influence. The test is rapid to set-up and conduct relative to a slug test and is applicable in both the saturated and unsaturated zones. The test yields an average interval value for hydraulic conductivity. Equipment compliance and wellbore storage effects are not generally observed as the pressure differential is constant. In this test, if flow rates are high, pressure loss along the pipeline to the ground surface due to frictional losses is another important consideration.

Additional factors which may influence the accuracy of injection tests, such as leaky packers, temperature induced pressure responses, skin effects, etc. are discussed in detail in Section 2.4.3.

(iv) Spinner Flowmeter Test

The spinner flow meter test is based on the correlation between the velocity of borehole fluids and the hydraulic conductivity. This test involves measuring water velocity versus depth in the pumping well and relating the incremental flow increase to hydraulic conductivity variations. Inflow of water to the borehole from the matrix shows up as a gradual increase in velocity with elevation whereas single fractures or fracture networks show up as a step increase in velocity. The actual fissure hydraulic conductivity cannot be determined, only the average value for selected borehole intervals. Test results must be corrected for borehole diameter variations prior to test data analysis.

Testing conducted in the NAGRA deep borehole testing program in Switzerland by the Geologic Survey of Denmark found the test to be further limited to test hole sections where the velocity is higher than 0.1 m/min due to the range of measurement of the 90 mm Spinner Flowmeter Tool (Bull, 1984). Thus, the test is usually used in higher hydraulic conductivity fractured rock environments.

(v) Labelled Slug Test

The labelled slug test is a method used in conjunction with the Spinner Flowmeter Test (previous section). The method is used to assess the permeability profile in single boreholes where the hydraulic conductivity is too low to facilitate measurement of velocities in the borehole (i.e., use of the Spinner Flowmeter Test). A conservative (i.e., non-reactive) tracer is injected into selected intervals of the borehole and the formation prior to the test. Pumping then commences jointly with tracer concentration measurements along the

borehole. The changes in tracer velocity, which are indicative of water velocity, are a function of only the inflow from the formation and the changing borehole diameter. Borehole diameter variations may be accounted for with a knowledge of borehole diameter with depth from caliper logs. The water velocity distribution is obtained by continuously measuring the concentration of tracer at various depths and times.

Laminar flow is assumed in the borehole. The velocity profile over the diameter of the borehole is parabolic and the arrival time of the tracer must be corrected for average velocity. The rate of tracer movement over selected intervals provides an indication of the hydraulic conductivity throughout the borehole length.

2.4.1.2 Multiple Borehole

(i) Interference/Injection Tests

The single hole test methodologies discussed in section 2.4.1.1 have, in a number of instances, been modified to involve multiple hole tests. The rationale for multiple borehole injection tests is to characterize the three-dimensional permeability tensor as opposed to the one-dimensional fracture or average two-dimensional radial hydraulic conductivity obtained with the single well tests. In addition, multiple hole injection tests or interference tests are representative of a much larger rock volume, the scale of which is related to the distance between the test and monitoring wells. Thus, multiple borehole tests tend to be more representative as the volume of rock sampled is larger and conditions in the immediate vicinity of the borehole (i.e., borehole skin effects) have less of an impact on test results.

Pressure pulse tests can also be utilized in interference testing where the pressure pulse is applied at one borehole location and the pressure response is monitored in another borehole.

A number of researchers have developed methodologies for conducting and analysing multiple well injection tests. Most notable of these are those developed by Snow (1966), Louis (1974) and Hsieh et al. (1983). Snow (1966) developed a technique called the "three-hole pressure test". Snow's methodology involved conducting separate injection tests in each of three boreholes each oriented along one of the principal directions of hydraulic conductivity. However, this test required a previous knowledge of the principal directions of hydraulic conductivity prior to drilling boreholes. Also, drilling of the boreholes at the required orientations may be difficult (i.e., near horizontal).

Louis (1974) proposed a different method for determining anisotropy in hydraulic conductivities which requires one test hole and two monitoring holes all along one of the three principal directions of hydraulic conductivity. The monitoring holes are then located such that, on a plane normal to the axis of the three holes, the lines connecting the monitoring wells to the test well lie parallel to the two remaining principal directions of hydraulic conductivity. Louis' method utilizes a guarded straddle-packer to ensure radial flow out from the test interval. The hydraulic conductivity for the two principal directions perpendicular to the axis of the test hole are determined from the injection rate and the pressure response in the monitoring wells. The hydraulic conductivity for the direction parallel to the boreholes is determined from the total injection rate

(test interval plus guard intervals) in conjunction with the two previously computed hydraulic conductivities. Louis's method suffers from the same problem as Snow's in that the principal directions of hydraulic conductivity must be known prior to drilling the boreholes and the drilling of boreholes at the appropriate orientation may be difficult. However, a greater rock mass is sampled so that the hydraulic conductivities determined may be more representative of a larger scale.

An injection testing methodology which facilitates determination of the three-dimensional values of hydraulic conductivity has been developed at University of Arizona (Hsieh et al., 1983). The method, referred to as the cross-hole test, is sufficiently general that the principal directions of hydraulic conductivity need not be known prior to conducting the test. Fluid is injected into a relatively high hydraulic conductivity interval in one borehole and the response is monitored at an array of adjacent boreholes. The arrangement of the boreholes, of which six are required, is relatively flexible provided that no more than two observation points lie along a line or no more than three observation points lie in a plane. The isolated intervals may be treated as either point sources or line sources depending on their length.

The cross-hole test is advantageous in that it is representative of a much larger rock mass than single hole tests, it allows an assessment of the validity of the continuum approach (i.e., if a polar plot of directional K 's delineates a distinct ellipsoid, the continuum approach holds) and it may detect the presence of major faults or fractures in the vicinity of the test interval. Furthermore, an indication of single versus dual porosity flow may be identified.

The results of the fluid injection are analyzed for steady state conditions by considering the rock mass as a uniform anisotropic porous media. The observed response is compared to the predicted response to obtain the six independent components of the hydraulic conductivity tensor. A graphical solution is available if a point source assumption is valid for the monitoring and injection intervals. Otherwise, computer based matching is required due to the large number (seven) of parameters to be determined.

(ii) Pump Test

Pump tests involve inducing a perturbation to the hydrogeologic regime through removal of water at a constant flow rate through a partially or fully penetrating well. The response of the hydrogeologic system is monitored at observation wells situated at various radial distances and orientations from the pumping well within the same hydrostratigraphic unit. Response may also be monitored at the pumping well itself although the pumping well response is subject to wellbore storage effects which may have to be accounted for in the analysis stage. The parameters determined are the hydraulic conductivity and storativity provided the transient portion of the observed data is analysed.

The range of hydraulic conductivities in which pump tests are applicable is between 10^{-9} and 10^{-4} m/s according to Wilson et al. (1979).

A number of data analysis techniques have been developed for the purpose of interpreting pump test data. These techniques range from simple analytical solutions developed for porous media to more sophisticated numerical models for

fractured media (e.g., dual porosity models). The majority of the analytical solutions incorporate a number of assumptions to simplify the physical problem to the point where it can be solved analytically. These include assumptions regarding the aquifer extent, aquifer homogeneity, pumping rates and well screen extent.

The most frequently used pump test analysis techniques are those of Theis (1935) and Jacob (1950). The Theis (1935) method utilizes an analogy to heat flow to obtain an analytical solution to the differential equation governing flow to a pumping well. The hydraulic conductivity and aquifer storage are obtained from a matching of the observed drawdown data to a number of dimensionless type curves.

The major problem associated with the Theis method is that the observed data may be fit to a number of type curves of similar shape. Also, fulfillment of all of the assumptions inherent in application of the method is not likely in actual practice, particularly in fractured geologic media.

Jacob (1950) found that for a sufficiently long time since the start of the test and for small radius wells the infinite series of the Theis solution can be reduced to only three terms without serious error.

Alternate approaches have been developed by Popadopoulos (1965), Hantush (1966a,b) and Hantush and Thomas (1966) who developed analytical solutions for pump tests for aquifers

having their principal directions of hydraulic conductivity in the vertical and horizontal planes. Weeks (1969), Neuman (1975) and Way and McKee (1982) developed similar techniques for both confined and unconfined aquifers with the same limitations pertaining to the principal directions of hydraulic conductivity. All of these solutions were developed for porous media applications. Many researchers, however, have applied these techniques to fractured rock systems to obtain equivalent porous media permeabilities. The difficulties associated with applying such porous media models to fractured media are discussed in detail in Section 2.4.3.

A number of analytical expressions have been developed expressly for the purpose of analysing pumping tests in fractured rock systems. Some of these solutions are merely extensions of porous media homogeneous models to include the anisotropy present in fractured rock systems (e.g., Prats, 1972; Saad, 1967). Other solutions have been obtained for the situation in which a high permeability fracture intersects the wellbore. Most notable of these is Gringarten et al. (1974). This solution employs numerous assumptions in order to obtain a solution to the flow equation. Some of the assumptions pertain to fracture characteristics and include assuming that the wellbore intersects a single plane fracture of infinite extent. Variations to the original solution have been developed to account for wellbore storage and skin effects (Ramey and Gringarten, 1975). Gringarten (1982) classifies the remaining models used to characterize fractured rock systems as heterogeneous models and includes in this category double porosity, multilayer and composite models. Double porosity models are based on the approach proposed by Barenblatt et al. (1960). This model assumes the

existence of two regions (fracture and matrix) of different permeabilities and porosities. The original Barenblatt et al. solution assumed that matrix storage was negligible. Subsequent solutions to this equation (e.g., Streltsova-Adams, 1978) have included this effect. The multilayered model represents the fractured rock system as a series of uniformly spaced matrix and fracture layers. This approach can be identical to the double porosity model and has been used by Kazemi (1969) and Boulton and Streltsova (1977). An alternate approach (Hurst, 1960) has been used to simulate the effect of a fractured rock system. In this approach the fracture system is represented by two concentric homogeneous isotropic regions of different permeability.

(iii) Macroscopic Hydraulic Conductivity Tests

Macroscopic tests involve interpreting a value for hydraulic conductivity from large scale perturbations to the ground water system. This type of test may be referred to as drainage tests or large scale crustal permeability tests. Flow measurement and piezometric elevations induced by construction excavation and subsequent dewatering (e.g., mine shafts) allows assessment of a large rock volume and acts as a check on tests at a smaller scale. Macroscopic testing provides an indication of whether or not a representative elementary volume is being sampled by the smaller scale tests.

Large scale testing of this nature has been utilized at the Stripa site (Wilson et al., 1979). Problems with this type of testing arise from the difficulty in monitoring flow rate which originates from a large surface area (e.g., ventilation shaft).

(iv) Fracture Sampling Method

The fracture sampling method is an approach developed to estimate the hydraulic conductivity tensor based on the parallel plate approach of Snow (1966) and Romm and Pozinerko (1963). The approach involves projecting fracture orientations on a stereonet to identify fracture sets. An equation is then used to infer hydraulic conductivity tensor from aperture characteristics. The information needed includes orientations, spacings, apertures and roughness of fractures which may be obtained from outcrops, cores, borehole geophysical logs (i.e., acoustic televiewer) and single hole packer tests straddling individual fractures. Field applications of the method are presented in Bianchi and Snow (1969) and Parsons (1972).

Problems with the method include the reliability of measurements of fracture parameters as well as the differences between the idealized and actual system. Fractures of constant aperture, infinite extent, equal spacing and parallel orientation are not likely to occur in nature. They may also be infilled with minerals. Measurement of fracture aperture, even in underground openings, will likely not be indicative of in situ values due to the release of stress by the sampling technique.

2.4.2 Laboratory Test Methods

Hydraulic conductivity testing in laboratories is oriented towards assessing the hydraulic properties of individual fractures and cores. Laboratory test methods, in many instances, consist of essentially the same methods as those utilized in the field except that the test environment is

more readily monitored and/or modified. The following sections discuss the most widely used laboratory test methods.

(i) Permeameter Tests

Permeameters may be classified as either a constant-head permeameter and falling-head permeameter.

For constant-head permeameter tests, the head and consequently flow rate is kept constant and the change in hydraulic head across the test sample is monitored. This test is used in more permeable media and is reported to be best suited to samples with hydraulic conductivity greater than 2×10^{-6} m/s (Klute, 1965); however, Trimmer et al. (1980) suggest that the range of application of the test, in intrinsic permeabilities, is 10^{-11} to 10^{-18} m² (6×10^{-12} to 6×10^{-5} m/s at 5°C).

The constant head tests used in the lab are analogous to those used in the field with the exception that the lab version is an assessment of the one-dimensional properties of the sample whereas the in situ version samples radial properties. The sample is positioned in a cell and the flowrate is monitored for constant pressure gradient across the sample. Once steady-state conditions are achieved, the results are recorded and analyzed (see for example, Forster and Gale, 1980a).

Forster and Gale (1980b) applied the constant head (injection) test to a core of Stripa Granite with a single natural fracture parallel to and centered in the core axis. The results were found to be comparable to pressure-pulse testing on the same core.

The falling head test is a transient test in which the water level is dissipated with time in a water column connected to and draining through the sample. This test is used for material of lower hydraulic conductivity than the constant head test. The use of this method for hydraulic conductivity testing in fractured media is not well documented in the literature.

(ii) Pressure-Pulse Tests

Pressure-pulse laboratory tests are again similar to those conducted under field conditions with the difference being that the hydraulic properties are indicative of only the direction parallel to the axis of the core sample.

Laboratory tests are representative of hydraulic properties at the scale of the sample size. Applicability to a larger rock volume should be verified by field testing.

Laboratory pressure-pulse testing is useful in that it can be used to quantify the effects of packer compliance which may subsequently be factored out of field test observations. Through pressure-pulse testing of a sample with a natural fracture, Forster and Gale (1980b) found compliance effects lead to an underestimate of hydraulic conductivity by a factor of up to two.

Pressure-pulse tests were first widely used by Brace et al. (1968). The technique developed by Brace et al. is reported (Trimmer et al., 1980) to be applicable to assessing intrinsic permeability in the range between 10^{-17} and 10^{-21} m^2 (10^{-10} to 10^{-14} m/s @ 5°C) to within 5%. The test was modified slightly by Trimmer et al. (1980) to determine intrinsic permeabilities in the range of

10^{-20} to 10^{-24} m² (10^{-13} to 10^{-17} m/s @ 5°C).

Test modifications involved curtailing testing prior to reaching equilibrium due to the long time required for equilibrium to be established (two weeks to six months). The test ceased when pressure changes were less than 0.1 MPA in one week. Trimmer et al. (1980) estimated that this introduces an error of less than 10%.

Analysis of pressure pulse tests may be conducted using either an analytical solution which neglects storage or a numerical solution which accounts for storage. The storage term may be neglected without affecting the analytical results when the sample volume is small relative to the reservoir volume. The value of hydraulic conductivity is obtained by matching observed to predicted pressure responses. Trimmer et al. (1980) recommend matching data on the steepest portion of the curve as the thermal transient induced by the initial pressurization has likely dissipated by this time. Furthermore, this portion of the curve gives maximum resolution and is relatively insensitive to the storage term.

(iii) Large Core Injection/Withdrawal Tests

Laboratory testing of large diameter core is an approach adopted by some workers (Thorpe et al., 1980; Gale, 1977) in order to establish the hydraulic properties of samples under controlled laboratory conditions at a scale larger than conventional lab tests.

Thorpe et al. (1980) conducted steady state injection tests in a simulated borehole through a large (1 m diameter by 2 m length) sample of the Stripa Granite. The ends of the test section were blocked using packers and the pressure was monitored in the test section and at the outer radius of the

sample. A triaxial test apparatus was used which facilitated conducting the test at a number of axial stresses typical of those encountered in situ. Precautions were taken to prevent over-pressurization of the void spaces by maintaining the water pressures at levels small relative to the axial stress applied.

Analysis of the test results indicated that single fracture permeabilities (hydraulic conductivity) determined for the Stripa Granite, were on the order of two orders of magnitude greater than previously determined values for fractured rock using both in situ and laboratory testing. A number of possible reasons were proposed to explain this difference, including boundary conditions differing from those encountered in situ and blasting and excavation affecting the hydraulic conductivity of the sample. In addition, Thorpe et al. (1980) indicate that one of the principal fractures in the core was separated during sampling.

It is also of interest to note that Thorpe et al. (1980) also came to the conclusion that flow simulation using a parallel plate analogy is a gross over-simplification of the complex flow of water through fractured rock systems.

2.4.3 Uncertainty Considerations in Hydraulic Conductivity Testing

Various factors may influence the measured pressure responses during hydraulic testing and thus may influence the determinations of the formation hydraulic parameters (i.e., formation pressure and hydraulic conductivity). These factors may have significant effects on the calculated value for hydraulic conductivity and should be considered in either

conducting or reviewing hydraulic testing programs. The most significant of these factors, from a summary by Grisak et al. (1985), are discussed in the following sections.

2.4.3.1 Conceptualization and Assumptions Regarding the Flow Regime

For conceptualization purposes, the flow regime during hydraulic testing in rock is often assumed to be analogous to a confined porous medium aquifer. In the analogy the packers which isolate the test interval are considered coincident with the confining units of the aquifer. The test interval represents the aquifer in which groundwater flow to or from the interval occurs radially.

Using this conceptualization, the following simplifying assumptions are adopted:

- (1) The aquifer (test interval) is confined, infinite in areal extent and constant in thickness;
- (2) The aquifer is homogeneous;
- (3) Areal flow in the aquifer is negligible;
- (4) Initially, constant head exists across the aquifer;
- (5) No vertical component of flow exists in the aquifer.

These assumptions have been universally applied in ground water problems in porous media to simplify the flow regime in a manner that is conducive to analysis. However, in terms of the conceptualization of the flow regime each assumption and its validity is worthy of further discussion.

Assumptions, such as a confined aquifer of infinite areal extent and constant thickness, provide sources of uncertainty with regard to the proposed conceptualization. The packers, although they isolate the interval do not confine flow in the formation nor do they limit flow in the formation to a specific thickness. The resulting effect during pressure dissipation or flow to or from the interval is that at each end of the interval, in the region of the packers, the flow regime is sub-horizontal as opposed to horizontal as it is in the centre of the interval. Thus, the tested zone affected by the flow is larger than that assumed using a constant thickness equal to the test interval length. The effect on a hydraulic conductivity determination is to yield a value that is larger than would be obtained in a totally confined system. However, this effect is likely to be dependent on the length of the test interval relative to the borehole diameter and volume of rock being influenced by the test (i.e., radius of influence). With a short interval (e.g., 1 metre) the end effects may be significant whereas for a long interval (i.e., several metres to 10's of metres) the end effect would be negligible.

The assumption of infinite areal extent in terms of the conceptualization should be examined carefully and will be valid if the zone of influence in the formation during testing is small in comparison to the total extent of the formation.

The homogeneous aquifer assumption is one that is commonly used in ground water problems but is rarely achieved in reality. Heterogeneity in crystalline rock is difficult to quantify. However, unless the nature of the heterogeneity can be defined the assumption of homogeneity along the test interval length provides the simplest and possibly the most reasonable description of the spatial variation of hydraulic conductivity (i.e., for the purpose of hydraulic conductivity profiling).

The assumption which states that areal flow in the formation is negligible, is an assumption that is justifiable when one considers the low flow rate in the formation under natural conditions (i.e., under low gradients) compared to the high gradients and flows that are induced in the formation interval due to the hydraulic testing procedures (i.e., pulse, slug or pump tests).

Constant hydraulic head across the aquifer is an assumption that is justifiable outside of the zone influenced by the drilling and pretest borehole pressure history. The hydraulic head in the immediate area of the borehole is likely to be affected by borehole history and result in the formation exhibiting dramatic differences in hydraulic head with short distances from the borehole. The effects of borehole pressure history are discussed further in a later section of this report.

The assumption of no vertical component of flow existing in the aquifer can be addressed in a manner similar to that of the first assumption. Although some vertical flow in the aquifer may occur near the packers its effect in terms of the entire length of the test interval is likely to be small.

Vertical flow which may occur naturally in the formation is likely to be of a small magnitude as compared to the horizontal flow induced by the hydraulic testing.

The assumptions as discussed above cause some uncertainty in the results but are necessary to transform the field situation into a conceptual model that allows an analysis of the field measured pressure data to determine formation hydraulic parameters. Where test intervals on the order of several metres are used, the assumptions are generally appropriate but the confidence in the results may decrease as the test interval becomes much shorter or much longer. The influences on the formation parameter determinations associated with measurement scale are discussed in a later section.

Another assumption commonly employed in the analyses of well tests is that the radius of the well itself is small implying that wellbore storage effects are negligible. The magnitude of the error introduced by such an assumption will be governed by the physical parameters of the media (e.g., formation permeability and compressibility), the nature of the test (e.g., duration) and the size of the wellbore. Some analytical (e.g., Papadopoulos and Cooper, 1967) and numerical solutions can account for such wellbore storage effects.

2.4.3.2 Porous Media Versus Fracture Flow Analyses

The use of fracture flow models, such as the solutions published by Wang et al. (1977), are somewhat restrictive in that the theory is based on very idealized assumptions regarding physical conditions, such as the existence of either a single fracture or a known number of identical contributing fractures (from a hydraulic perspective) within the test interval. Such an understanding of the most important fractures within a test interval is rarely, if ever, attained.

Fracture flow and porous media analysis methods based on implementation of the Wang et al. (1977) and Bredehoeft and Papadopoulos (1980) analytical solutions can be utilized to compare the ideal responses from these two flow conceptualizations. The calculated pressure responses for the two analytical solutions have notably different shapes. The difference in pressure responses are a consequence of the assumptions involved in the two conceptualizations. The Wang et al. (1977) solution is based on the assumption of flow or pressure dissipation from the packer-isolated borehole interval into a single fracture surrounded by essentially impermeable rock. In the fracture flow conceptualization, the driving force for flow (resulting in pressure changes) from the wellbore into the fracture is the result of the compressibility of the water only, whereas for the porous media case compressibility effects are accounted for in both the water and the rock.

Barker and Black (1983), having found similar results, state that in reference to fracture models versus porous media models, the porous media model has a "derived aquifer transmissivity (that) will always be over-estimated, but by a factor which is unlikely to exceed three".

2.4.3.3 Radius of Influence

The radius of influence or the extent of the formation that is being hydraulically tested is an important consideration when evaluating the representativeness of the interpreted hydraulic conductivity value compared to the actual value of the rock formation. As with physical measurements on any natural system, uncertainty will always exist as to the representativeness or transferability of the measurement scale to larger scales of interest.

To provide an indication of the relative amounts of rock mass sampled by various testing techniques the results of various test analyses from Grisak et al. (1985) have been reproduced herein. Using representative crystalline rock and formation fluid properties, the radius of influence was calculated for pulse and slug tests over a range of hydraulic conductivity values. For the purposes of this analysis, the radius of influence was defined as corresponding to a pressure change equal to 10% of the borehole pressure pulse.

The results of the pressure pulse analyses are presented below:

Hydraulic Conductivity (m/s)	Radial Distance of Tested Rock (cm)	
	6 hour test	12 hour test
1×10^{-11}	43	43
1×10^{-12}	41	42
1×10^{-13}	18	25

The radial distance of tested rock for hydraulic conductivities less than 1×10^{-11} m/s is in the range of 18 to 43 cm for hydraulic testing. The testing of these radial zones of rock was considered sufficient to obtain good hydraulic conductivity estimates of the rock formation as the radius of influence extended beyond the expected radius of any skin effects or erosion of the borehole.

The radius of influence determinations for the slug test analyses are summarized below:

Hydraulic Conductivity (m/s)	Radial Distance of Tested Rock (m)
10 ⁻⁶	18
10 ⁻⁸	20
10 ⁻¹⁰	4

The radial distance of tested rock during slug tests is on the order of 4 to 20 m. While the fact that the largest radius of influence corresponds to an intermediate permeability value may appear strange this is not an anomaly. It can be explained by two permeability related processes. In the high conductivity case, the radius of influence is controlled by the ability of the formation to supply water to suppress the cone of depressurization. In the low permeability case the radius of influence is controlled by low permeability itself limiting the ability of the pressure perturbation to move through the formation. In general, slug tests, because of the large radial distances of tested rock, provide hydraulic conductivity values that are typical of the rock far outside of any zones affected by drilling or skin effects.

2.4.3.4 Orientation of Fractures or Higher Permeability Zones

Fractures (or higher permeability zones) intersecting the borehole at a right angle will produce a pressure response that is different from a zone of similar aperture (or thickness) that intersects the borehole at an angle less than 90°. For a subhorizontal fracture the wellbore - fracture contact is an ellipse rather than a circle and therefore has a larger contact area. Because the contact area is larger the pressure recovery will be faster producing an overestimation of hydraulic conductivity above that which would have been obtained for a similar horizontal fracture. Therefore, without knowing the orientation of a fracture

which is contributing to the hydraulic conductivity of an interval, the hydraulic conductivity may be subject to some uncertainty. The magnitude of this uncertainty will increase for larger deviations from the horizontal. For example, from theoretical results presented in Wang et al. (1977), it can be estimated that the aperture would be over-estimated by a factor of 1.2 for a fracture at 66° to the horizontal or equivalently an over-estimate of hydraulic conductivity by a factor of 1.7.

2.4.3.5 Borehole Diameter

The borehole diameter is a parameter required for data analysis that is subject to variation from the original drilled diameter and, therefore, presents an additional source of uncertainty. The variation in the diameter of the borehole is due to erosion of the borehole wall due to the rotation of the drill rods within the borehole, the removal and insertion of drill equipment in the borehole and the circulation of borehole fluid. In areas of softer crystalline rock or poor rock quality, the erosion of the borehole wall can be significant.

Calculations were conducted using a computer implementation of the Bredehoeft and Papadopoulos (1980) and Cooper et al. (1967) analytical solutions to quantify the effects of uncertainty in borehole diameter when analyzing hydraulic pulse and slug test data and are reported in Grisak et al. (1985). The results of these simulations are presented in Figure 2.7 and indicate that by varying the borehole diameter and the formation hydraulic conductivity approximately the same curve could be reproduced. It can be seen that for representative formation properties a 25% increase in borehole diameter (from 0.159 m to 0.20 m) resulted in a 66% increase in the estimated hydraulic conductivity value (from 6×10^{-12} m/s to 1×10^{-11} m/s).

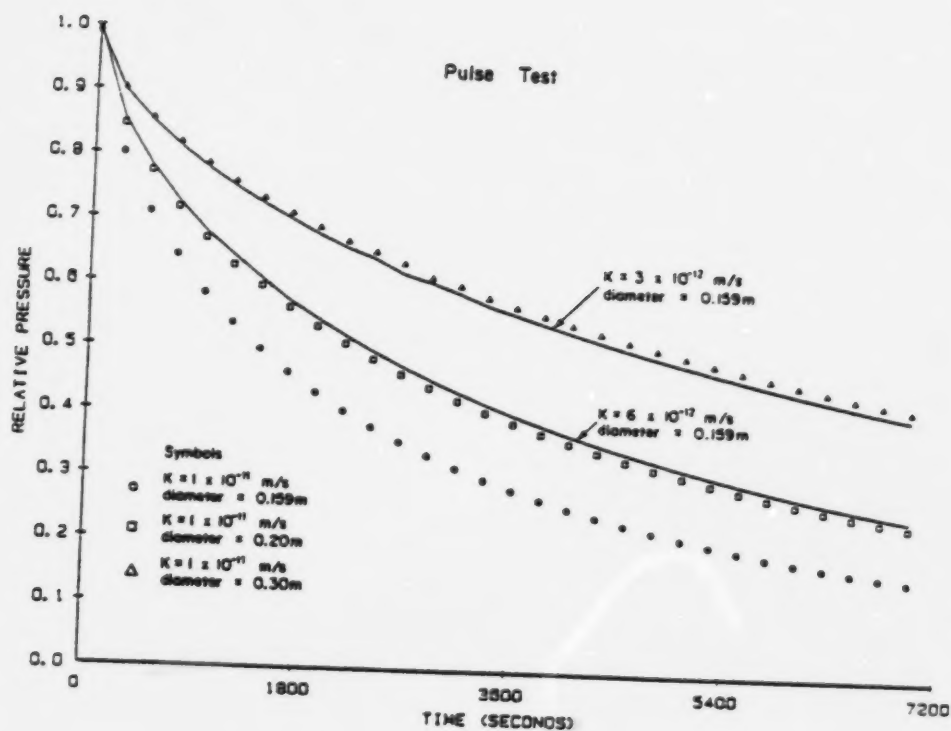


Figure 2.7 Calculation of the Effect of Borehole diameter on normalized calculated pressure response for a pulse test using the Bredehoeft and Papadopoulos (1980) analytical solution (Grisak et al., 1985)

2.4.3.6 Higher or Lower Permeability Skin Surrounding the Borehole

Skin effects on the borehole wall or immediately surrounding the borehole are possible sources of uncertainty. A higher permeability skin could develop on the borehole wall due to erosion caused by drilling or dissolution of minerals caused by circulated drilling fluids. Lower permeability skin effects may be caused by drilling fluid or rock flour (present in the borehole due to drilling) clogging or blocking fractures, cracks or pores in the formation or even by the precipitation of infilling materials in fractures or pores.

In crystalline rocks, as opposed to sedimentary rocks, skin effects are usually not as significant. The harder, denser crystalline rocks will resist erosion to some extent although it is still likely to occur. Dissolution of minerals in the borehole wall is also a less significant effect in crystalline rock. Because crystalline rocks are not drilled using drill mud, clogging of the formation should be minimized.

The influence, or magnitude, of skin effects is difficult to quantify but are likely related to the radius of influence described previously. If the radius of influence is large then skin effects may be less significant and the hydraulic conductivity determined from the interval will be representative of the formation rather than the borehole skin. On the other hand, if the radius of influence is small or the skin affected zone is thick, then the hydraulic conductivity is likely to be influenced by that of the borehole skin.

2.4.3.7 Formation Pressure

Hydraulic test data analysis for the purpose of determining hydraulic conductivity estimates requires that a unique reference pressure be either chosen or determined as part of the type-curve analysis procedure. The chosen or determined reference pressure must be carefully evaluated and take into consideration the following:

- estimated formation pressure (either from measured pressure response for the tested interval or estimated from the expected hydraulic head based on comparison with adjacent test intervals with measured formation pressures);
- annulus pressures;
- duration of and pressure fluctuations during the borehole pressure history period.

The use of hydraulic test data analytical methods which include the effect of borehole pressure history generally allows a more accurate representation of borehole and formation pressure responses during testing. These analytical methods, while usually more time consuming, are justified for cases with borehole open periods from hours to weeks between drilling and testing, or where significant pressure fluctuations are imposed on a test interval during a testing sequence.

The pressure within the borehole after drilling a test interval (referred to as annulus pressure) will, in general, be different from the in situ formation pressure. This pressure difference results in the development of a pressure

skin surrounding the borehole that is different in magnitude from the formation pressure. The net effect of the "pressure skin" developed during the drilling and pretest period may be the violation of the assumptions involved in type-curve analytical methods based on analytical solutions of the radial flow equation. Analytical techniques have been developed to account for pretest borehole history (Grisak et al., 1985) provided sufficient information regarding the pretest history is available.

2.4.3.8 Thermally-Induced Borehole Pressure Response

During drilling and testing of deep boreholes, a temperature gradient may be developed into the formation in response to the differential temperatures between the borehole fluid and the rock. These temperature gradients in the formation may cause a variation in the borehole fluid temperature during the hydraulic testing period. These temperature variations result in significant pressure changes during pulse testing (i.e., under shut-in conditions), especially in low permeability formations as a consequence of the thermal expansion (or contraction) of the fluid.

Analytical methods have been developed to account for thermally-induced pressure effects to allow more accurate formation pressure and hydraulic conductivity estimates to be determined from the test data (Grisak et al., 1985).

2.4.3.9 Accuracy of Equipment Readings and Depth Measurements

The magnitude of uncertainty in testing equipment should be considered in all pressure measurements and pressure responses used in hydraulic conductivity determinations.

These considerations should include such uncertainties as the resolution and accuracy of measurement devices such as, temperature and pressure transducers. Lynes, Inc., a manufacturer of downhole pressure testing equipment, reported the accuracy for their pressure-temperature probe as follows (Lynes, 1984):

<u>Operating Range</u>	<u>Absolute Accuracy</u>	<u>Resolution</u>
0 - 125°C	$\pm 1^\circ\text{C}$	0.1°C
0 - 6000 PSIA (0-41370 kPa)	$\pm 0.05\%$ Full scale	0.005% Full Scale

The reported accuracy of the pressure transducer is about 20 kPa or about 2 m of water.

2.4.3.10 Testing Procedures and Equipment Difficulties

Testing procedures should be utilized which will provide suitable hydraulic test data for hydraulic conductivity determination. Examples of problems which may occur include:

- poor initial conditions (insufficient pressure differential) for pulse and slug tests;
- shut-in squeeze during closing the shut-in tool for the pressure build-up period of a drill-stem test;

- equipment difficulties or malfunctions (e.g., leaking shut-in tool; packers slipping on borehole wall; packer deflation or rupture);
- streaming of fluid down the bore of the tubing string during a flow period;
- insufficient overlap of adjacent test intervals.

Hydraulic tests should be designed and monitored to minimize the above types of problems. Careful examination of the measured pressure responses during testing is necessary in order to identify testing problems and take appropriate action (e.g., equipment replacement; repeating the previous tool movement in order to obtain the correct initial conditions for a test). When a testing problem is identified after the test has been completed, it may be necessary to re-test the corresponding borehole interval. During the analysis of all hydraulic tests, the possibility of the above-noted testing problems should be assessed as part of the data interpretation/evaluation phases before recommendations are made with regard to the interpreted formation parameters.

2.4.3.11 Equipment Compliance

Virtually all test methodologies suffer from some type of equipment compliance due to the non-rigidity and, as a result, the deformation of the equipment components. Equipment compliance can be related to a number of things, including movement of packer assembly, cold-flow of packer rubber, entrapped air in the equipment located in a test interval, machined tolerances on the seating and positioning of various steel components and O-ring or other seals, etc.

In addition, test equipment that incorporate packers and measurement tools in the same assembly may be subject to operational compliance. For example, subsequent to packer inflation, the "shut-in" process results in a "shut-in squeeze" which is a pressure increase in response to a small fluid injection into the test interval. In addition to the shut-in "squeeze" the added weight must, of course, be supported by the packer, which is inflated against the borehole wall. Because the packer and downhole system are not totally rigid, the increased weight tends to "compress" the isolated interval.

In order to develop a quantitative capability for analyzing pressure test data which includes compliance effects, the magnitude and shape of the compliance function must be known. In the simplest case, the compliance can be treated as a step function, and either considered as part of the initial shut-in squeeze or applied subsequently. In more complicated cases the compliance is regarded as a time, pressure (both within, above and below the test interval) and load dependent mathematical function, with the shape and magnitude defined by several compliance related parameters.

2.4.3.12 Fluid Properties

Calculations involving hydraulic heads and formation pressures require estimates of the borehole fluid density. All formation pressures and hydraulic heads must be evaluated in a consistent manner to allow a comparison of the calculated hydraulic heads corresponding to the different test intervals or formations.

The variation in fluid density along the length of the borehole and between various formation depths is the most important factor affecting the interpretation of representative formation pressures.

The factors influencing fluid density are:

- pressure;
- temperature;
- salinity (dissolved constituents).

For analysis of the hydraulic test data for the determination of hydraulic conductivity, the density, viscosity, compressibility and thermal expansion coefficient (for some cases) of the in situ fluids are required. It is usually assumed that the borehole and formation fluids have the same properties. Measurement of the fluid specific gravity at surface conditions and temperature and pressure at in situ conditions allow the determination of relatively accurate estimates for density and viscosity for use in hydraulic conductivity analyses.

Fluid viscosity and thermal expansion coefficient exhibit the greatest variation with depth. Choice of representative fluid property values during test analyses is necessary to achieve as accurately as possible, estimates of hydraulic conductivity.

2.4.3.13 Approaches to Controlling Uncertainty

The various factors that should be considered when interpreting the measured pressure responses during hydraulic testing and thus the determinations of the formation hydraulic parameters (i.e., formation pressure and hydraulic conductivity) have been presented in the previous section. The uncertainty in hydraulic conductivity can be minimized by the careful examination of testing conditions (e.g., isothermal versus nonisothermal conditions) and testing procedures (i.e., identification and correction for poor

initial test conditions or equipment difficulties/malfunctions), choice of assumed parameter values (e.g., rock and fluid properties, reference pressure, storage coefficient), choice of appropriate data analysis methods (e.g., porous media versus fracture flow models; inclusion of borehole history and thermal effects), examination of borehole physical conditions (e.g., borehole erosion and possible skin effects) and examination of the appropriateness of the selected measurement scale (i.e., packer spacing).

Four approaches can be utilized to provide some quantification of the uncertainty associated with the hydraulic conductivity testing:

- (1) Examination of the repeatability of the interpreted hydraulic conductivity for a particular test interval using a series of tests in a testing sequence. Examination of results from repeat testing at a later time at or approximately at the same test interval depth may also be conducted;
- (2) Sensitivity analysis on the parameters involved for simulation of each borehole hydraulic test;
- (3) Sensitivity analysis on the hydraulic conductivity distribution utilized in local or regional scale groundwater flow model simulations;
- (4) Formal uncertainty analysis using equivalent stochastic models for parameter estimation.

3.0 SPECIFIC STORAGE PARAMETERS

3.1 Definitions

The equation describing groundwater flow through a porous medium is based on the law of continuity (conservation) of mass. For a homogeneous isotropic medium the mathematical formulation can be expressed (for a radial system) as (Theis, 1935):

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r} \frac{\partial h}{\partial r} = \frac{S_s}{K} \frac{\partial h}{\partial t} \quad (3-1)$$

where r is the radial distance from the borehole, S_s is the specific storage and h and K are as defined earlier (Section 2.1). In a truly steady-state hydrogeological system the change in water storage as a function of time is zero. In a transient system however changes in storage of groundwater within the media may be significant in determining the rate of response for the hydrogeological system. Typically the specific storage is comprised of two components, one representing the ability of the medium to deform as a function of pressure, the other representing the change of fluid mass contained within the pores of the medium. This latter quantity may be comprised of different components depending on the nature of the aquifer under consideration. In a fully saturated confined system the fluid portion of the storativity term is due solely to fluid compressibility and the specific storage (S_s) may be defined as:

$$S_s = \rho g (C_r + \phi C_w) \quad (3-2)$$

where ρ = density

g = acceleration due to gravity

C_r = rock compressibility

C_w = water compressibility

ϕ = porosity

The storativity (S) of a hydrostratigraphic unit is the volume of water released from the media per unit surface area per unit decline in head. It is related to the specific storage by:

$$S = S_s b \quad (3-3)$$

where b is the aquifer thickness. In a phreatic aquifer the dominant mechanism in determining the storativity is the volume of water released from storage due to the rise or fall of the water table. This mechanism, often termed the specific yield of an aquifer, can be described as:

$$S = \frac{\Delta V_w}{A \Delta h} \quad (3-4)$$

where ΔV_w is the volume of water released by a decline of Δh in the water table over an area A . The majority of the situations in which fractured rock environments would be considered would be most accurately described by an equation similar to Equation 3-2. Only in cases where the shallow groundwater regime is being examined in an area of rock outcrop would the contribution of water table storage be significant to the total specific storage.

3.1.1 Rock Compressibility

Examining Equation 3-2 it can be seen that the specific storage or storativity of any hydrogeologic medium is comprised (for fully saturated confined conditions) of fluid compressibility and rock compressibility terms. Rock compressibility is defined in a number of different ways by the scientific community. For example, hydrogeologists typically tend to normalize rock compressibility with respect to bulk volume. This yields an expression for C_r (see Narasimhan and Kanehiro, 1980) of:

$$C_r = \frac{1}{V_b} \frac{\delta V_v}{\delta \sigma} \quad (3-5)$$

where V_b is the bulk volume, σ is the effective stress and V_v is the pore volume. In the petroleum reservoir engineering literature the pore volume V_v is typically the basis for normalization instead of the total (bulk volume), enabling a pore volume compressibility (C_{pv}) to be defined, i.e.:

$$C_{pv} = \frac{1}{V_v} \frac{\delta V_v}{\delta \sigma} \quad (3-6)$$

Specific storage is also defined somewhat differently by the petroleum industry,

$$S_{spet} = \rho g \phi (C_{pv} + C_w) \quad (3-7)$$

If Equation 3-6 is substituted into Equation 3-7 one would obtain an equation identical to Equation 3-1 (after substitution into Equation 3-5).

Most of the rock compressibility data that exist in the literature has been evaluated for the purpose of doing rock mechanics analyses. This data is typically reported as either a Young's modulus (modulus of elasticity (E)) or a bulk modulus (B). Young's modulus is a measure of the uniaxial compression of a material in its elastic range and may be defined as:

$$E = \frac{\sigma_x}{\xi_x} \quad (3-8)$$

where: σ_x = uniaxial stress
 ξ_x = uniaxial strain

The bulk modulus (B) is a three-dimensional indicator of rock compressibility.

$$B = \frac{\sigma}{\frac{\Delta V}{V}} \quad (3-9)$$

If the system is isotropic (i.e., $\sigma_x = \sigma_y = \sigma_z$) then the bulk modulus of elasticity can be related to the Youngs modulus through the use of Poissons ratio (μ) which represents the ratio between transverse and axial strain. This relationship is:

$$B = \frac{E}{3(1 - 2\mu)} \quad (3-10)$$

If one assumes that the change in volume due to applied stress is due largely to the rearrangement of void space (a fairly reasonable assumption in as much as the compressibility of the rock grains themselves is fairly small) then the bulk modulus of elasticity may be related to the rock compressibility as:

$$C_r = \frac{1}{B} \quad (3-11)$$

3.1.2 Fluid Compressibility

Equation 3-1 indicates that two components of the specific storage exist. One of these is the fluid compressibility component which is comprised of the product of fluid compressibility and porosity. The fluid compressibility itself may be defined as:

$$C_w = \frac{1}{V_w} \frac{\delta V_w}{\delta P} \quad (3-12)$$

or simply stated as the unit change in fluid volume (V_w) with a unit change in pressure (P). Porosities may, in an analogous

fashion to permeabilities, be classified as either total, fracture or matrix. In general, porosity (ϕ) is defined in terms of a void volume (V_v) and bulk volume (V_b) as:

$$\phi = \frac{V_v}{V_b} \quad (3-13)$$

As indicated porosity forms an important component of the storativity of a hydrogeologic media. In addition, porosity is required to determine the average interstitial velocity of groundwater. This is relevant from the standpoint of calculating solute movement through the system. In fractured crystalline rocks porosity can be subdivided into matrix and fracture porosity:

$$\phi_T = \phi_f + \phi_m \quad (3-14)$$

Matrix porosity is typically that obtained from lab measurements on intact cores. Fracture porosity represents the contribution of either fracture zones or discrete fractures to the total void volume. Fracture porosity may be estimated by a number of techniques, the majority of which are in situ measurements. These include tracer tests and packer injection tests as well as estimates based on direct observation.

Some researchers (e.g., Norton and Knapp, 1977) have also used the concept of effective porosity, residual porosity or interconnected porosity to describe the effect of dead-end pore space. This can be included by reducing the magnitude of the

fracture and matrix contributions and adding an additional term to account for the residual pore space.

3.2 Influencing Factors

The various parameters that determine the specific storage of a geologic media (e.g., fluid density, porosity, rock and fluid compressibilities) are themselves functions of other variables. These variables are mainly temperature and pressure although other factors (such as solute concentration affecting fluid density) may be significant.

Fluid properties as a function of temperature, pressure and concentration are fairly well understood. The following discussion of these relationships has been condensed from INTERA (1981). The compressibility of pure water over the range of temperatures and pressures likely to be encountered in a repository design can be assumed to be constant, a value of $4.5 \times 10^{-10} \text{ Pa}^{-1}$ being representative. Sorey (1978) shows that while the thermal expansivity of water is virtually independent of pressure, its variation with temperature is significant. He recommends use of a quadratic expression to represent the fluid density dependence on temperature:

$$\rho = \rho_0 [1 - \beta(T - T_0) - \gamma(T - T_0)^2]$$

with $\beta = 3.17 \times 10^{-4}/^\circ\text{C}$ and $\gamma = 2.56 \times 10^{-6}/^\circ\text{C}^2$
for pure water.

This relationship was reviewed by INTERA (1981) and found to give excellent correlation to measured data. The variation of density with solute concentration is both non-linear and a function of the water chemistry. This fact is shown in Figure 3.1 which presents densities as a function of concentration (both molality and weight percent) for various solution types.

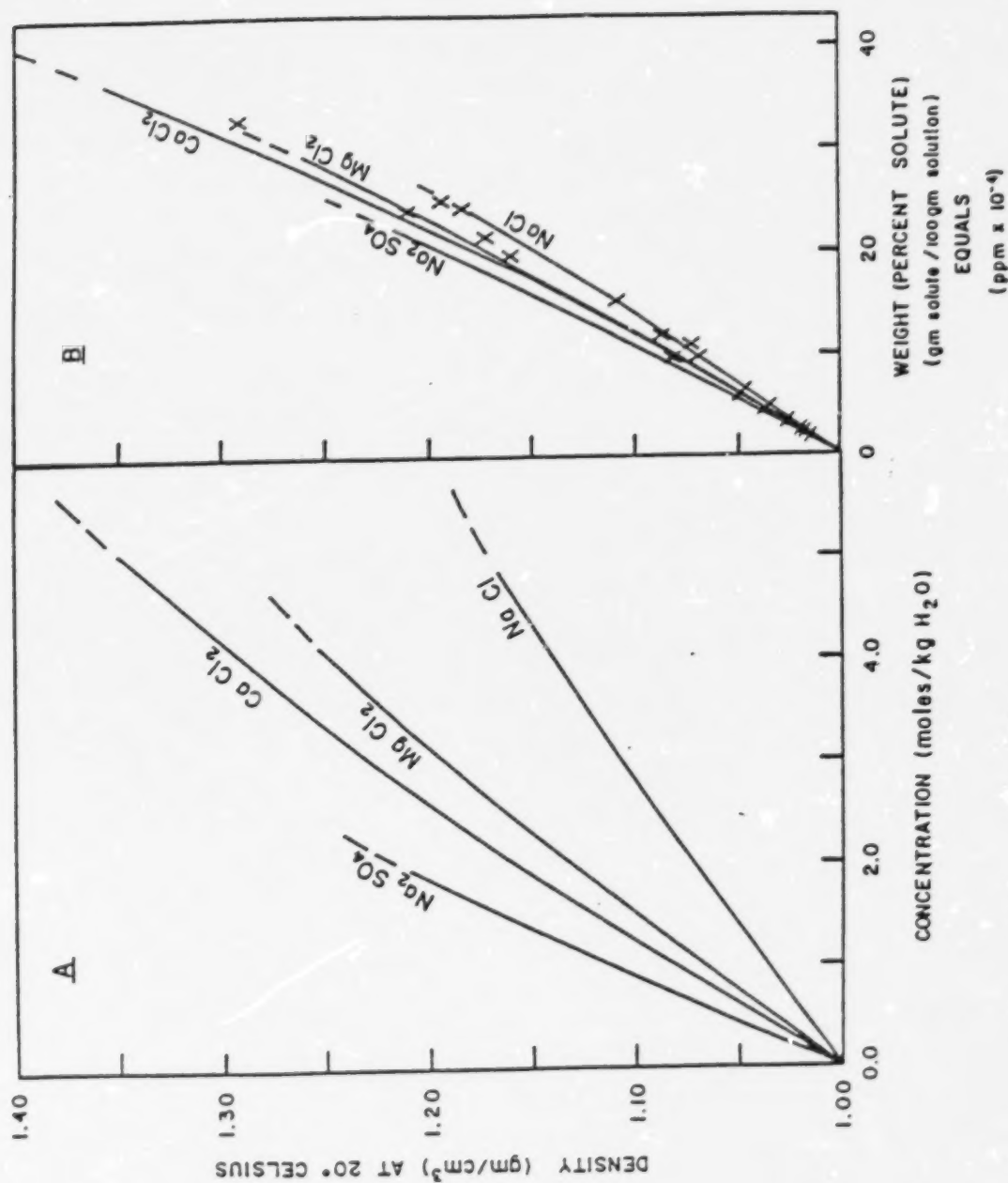


Figure 3.1 Solution density as a function of:
 A. Concentration
 B. Weight
 (after Intera, 1981)

As discussed earlier, the compressibility of a formation is related to its deformation moduli (either the Young's or the bulk modulus). Various researchers including Myer and Rachiele (1981), Page and Heard (1981) and Annor et al. (1981) have investigated the effect of temperature on the deformation moduli of crystalline rocks. From the results of these investigations it would appear that the relationship between deformation moduli and temperature is a function of the thermal expansion of the different component minerals. Curtis and Wart (1983) and Tammemagi and Chieslar (1985) indicated that the variation of Young's modulus due to temperature did not go beyond the range of values reported at ambient temperature and suggested this variability can be ignored for most applications.

Very little work has been done to investigate the relationship between porosity and either temperature or pressure. Page and Heard (1981) did attempt to relate porosity to temperature and pressure by comparing observed thermal expansivity to a theoretical value. While such an approach is very idealistic and should be used with caution, the results do provide a relative indication of the order of magnitude effect that can be expected due to such changes. As shown in Figure 2.1, the variation due to these influences are probably small compared to the variations that occur naturally.

3.3 Scale Considerations

Measurements of some of the parameters which affect the storage coefficient are influenced by the size of the sample being measured. In particular, measurements that are indicative of rock strength are known to be adversely affected by sample size (Pratt et al., 1972). This fact is generally attributed to the higher probability of a flaw or defect occurring in a larger sample size. Curtis and Wart (1983) indicate that this

relationship exists for deformation moduli as well (i.e., lower modulus values are obtained using larger samples) and suggest that this accounts for the lower deformation modulus values obtained as a result of in situ field tests.

It is unlikely that either bulk or matrix porosity values will exhibit any significant dependence on sample size. The reasons for this are the relatively small sample size required to obtain an REV coupled with the fact that matrix porosity comprises (by far) the highest proportion of the total porosity. The fracture porosity, on the other hand, is in many ways similar to the permeability measurements performed in fractured rock and the same points discussed previously (Section 2.3) regarding representative sample sizes are once again applicable.

3.4 Test Methods

3.4.1 Rock Compressibility

As discussed previously, rock compressibility can be obtained from estimates of either Young's modulus or bulk modulus. A number of techniques, such as downhole deformation tests and geophysical methods, can be used to estimate these parameters but by far the vast majority of the values reported in the literature are derived from laboratory measurements performed on cores. Uniaxial compression tests allow (when appropriate strain measurements are recorded) an estimate to be made of the modulus of elasticity (Young's). Triaxial compression tests are similar to uniaxial tests although in the triaxial case, the sample is subjected to a confining pressure.

A number of downhole techniques can be used to evaluate the in-situ deformation characteristics of a geological formation. These techniques may be classified as either direct

geomechanical tests or geophysical borehole techniques. Direct geomechanical tests usually consist of applying a load to the wall of a borehole and measuring the radial displacement. Devices which are used to apply this load and measure the resulting displacement include borehole jacks and dilatometers. The borehole jack was first used by Goodman et al. (1968) and is often referred to as the "Goodman jack". The instrument enables the elastic modulus to be calculated for a three inch (7.6 cm) diameter borehole by measuring the change in borehole diameter that occurs for a known pressure increment applied to opposite sides of the borehole through two eight inch (20 cm) long curved plates. Dilatometers differ from borehole jacks in that the load is applied uniformly over the borehole radius through the use of an inflatable membrane. Dilatometers have been used by a number of researchers most notable of which are Rocha et al., 1966 and Hustrulid (1976). There are difficulties associated with the use of both the borehole jack and dilatometers. For example, the Earth Technology Corporation (1985b) reported that both techniques have experienced difficulties in obtaining reliable estimates in deep boreholes (greater than 30 m). Variations in borehole diameter as well as borehole roughness can seriously impair the accuracy of these techniques. Hustrulid (1976) found that borehole/platen mismatch could result in a significant source of error for borehole jack tests, while Heuze and Salem (1976) indicate the longitudinal flexure of the platens could be significant. Shuri (1981) claims that neither of these explanations can possibly account for the consistently low values of elastic moduli determined by borehole jack tests.

Acoustic (or sonic) logging techniques are the main geophysical borehole method used to estimate deformation moduli of in situ rock masses. Acoustic logs provide an estimate of the travel

time for a compressional wave of acoustic energy to move through the rock surrounding the borehole wall. Using an estimate of the density of the formation (possibly obtained from a gamma survey) enables the deformation moduli of the formation to be calculated.

3.4.2 Porosity

Porosity of various geologic media can be estimated by a variety of techniques. Laboratory measurements may include various fluid displacement techniques (e.g. water, mercury) which together with density or caliper measurements can be used to calculate porosity based on the difference between oven dry and saturated samples. Brace et al. (1982) reported that this technique could yield accuracies to ± 0.001 . While immersion techniques account for the vast majority of porosity measurements reported in the literature, a number of alternate techniques have been employed by several researchers, including a methodology which uses a scanning electron microscope (Chernis, 1981) and well as a leach test method developed by Skagius and Neretniks (1983).

Other laboratory measurements for the determination of porosity include mercury infusion and grain density measurements (Evans, 1983). The mercury infusion technique consists of placing a sample into a mercury filled pycnometer and then measuring the quantity of mercury that intrudes into the sample when subjected to increasing incremental pressures. This method is subject to several sources of error, such as compliance of the pycnometer, compression of the sample and the inability of mercury to intrude pores smaller than 0.3×10^{-4} cm (Evans, 1983). Porosity determination from grain density measurements consists of pulverising samples to determine the density of the actual rock constituents. By knowing the original sample density (i.e., volume and weight) an estimate of the sample porosity can be made. Evans (1983) used both techniques on

samples of granodiorite and welded tuff, and found significant differences (an order of magnitude) existed for several samples. He attributes these differences largely to the inaccuracies associated with the mercury infusion technique as discussed above.

Several geophysical borehole logging techniques can be utilized to estimate the porosity of formations. The most common of these is the neutron log which uses a high energy source to bombard the formation with neutrons. The generated neutrons collide with nuclei present in the formation resulting in an energy loss. This loss is most significant for hydrogen nuclei and consequently the energy loss may be correlated to the water content of the formation. Energy loss is determined through the use of detectors which are capable of picking up gamma ray emissions (emitted due to the energy loss) or epithermal neutrons. Neutron logging techniques suffer from a number of problems including the fact they must be calibrated for each rock type, and may be biased by both natural gamma ray emissions and the existence of alternate forms of hydrogen. Neutron logging techniques have been used with varying degrees of success by Davison et al. (1982b), Nelson et al. (1979) and West et al. (1975).

Other geophysical logging techniques can be used to infer porosity from bulk density estimates by assuming a value for the density of the mineral grains. These techniques include gamma-gamma logging and borehole gravity meter logging. Electrical resistivity surveys have proven to be useful in providing bulk porosity estimates of pre-Cambrian rocks as reported by Brace et al. (1982).

Several researchers (e.g., Bianchi and Snow, 1969; Norton and Knapp, 1977) have estimated fracture porosity by assuming fractures are uniformly spaced planes of constant aperture.

Spacings and aperture sizes may be estimated by a variety of techniques including core logging and borehole televiewer. The accuracy of these approaches is somewhat uncertain. Suffice it to say that such an approach is based on an idealistic (and probably not a very realistic) set of assumptions regarding fracture characteristics.

Snow (1968) has also estimated fracture porosity using the results of packer injection test data. Using an equivalent set of assumptions to those stated above and calculating an equivalent aperture allows a fracture porosity to be calculated.

Two well tracer tests have become increasingly popular as a way of estimating effective fracture porosity. Tracer tests consist of introducing a dissolved chemical species into an isolated interval in a borehole. Transport of the tracer through the fracture(s) is monitored in selected intervals in other boreholes. Tracer tests are the only in situ hydrogeologic test which provides a measure of fracture porosity. Tracer tests are often used to determine interconnectivity, groundwater velocities and solute transport properties (i.e., dispersivity, retardation) in fractured media while at the same time providing a check on hydraulic conductivity. Tests of this nature have been conducted by Pickens and Grisak (1981), Marine (1980), and Novakowski et al. (1983) and involved locating interconnected fractures, identifying primary flow paths and confirming hydraulic properties previously determined.

Tracer tests may be conducted under either induced gradient or natural gradient conditions. Induced gradient tests include uniform gradient, radial divergent, radial convergent,

single-well injection/withdrawal, two-well injection/withdrawal, multiple well and in hole tests. Natural gradient tests include borehole dilution tests and tracer tests under ambient hydraulic gradients. The implications of whether natural or induced gradients exist may be significant in determining solute transport properties (i.e., dispersivity).

3.5 Range of Values

Fluid Compressibilities

The compressibility of water does not change significantly as a function of either temperature or pressure. In fact Pearson (1981) goes so far to state that over the range of temperatures and pressures of concern in repository design that the compressibility can be assumed to be constant at a value of $4.5 \times 10^{-5}/\text{bar}$ ($4.6 \times 10^{-10} \text{ Pa}^{-1}$).

Rock Compressibilities

Rock compressibility values tend to be significantly smaller than fluid compressibility values, in terms of their overall contribution to storage coefficient values. Consider for example a typical value for Youngs modulus - on the order of 60 GPa. Using a representative value for Poissons ratio (say 0.25) an estimate of the bulk modulus can be obtained using Equation 3-10 (on the order of 40 GPa). Using the relationship between compressibility and bulk modulus (Equation 3-12) one obtains a value for rock compressibility which is $2.5 \times 10^{-11} \text{ Pa}^{-1}$, a value significantly less than the water compressibility value quoted above. Due to the relatively insensitive nature of storage coefficient to rock compressibility only limited effort has been expended to collect rock compressibility related information.

The vast majority of the information that is available describing rock compressibility information has been collected by researchers concerned with rock mechanics investigations. The most commonly measured parameter is the modulus of elasticity (Young's modulus E) although Poisson's ratio and bulk modulus are also reported. Good sources of these values for crystalline rock types are obtainable from the reviews undertaken by Annor and Jackson (1982), Tammemagi and Chieslar (1985) as well as Clark (1966) and Dames and Moore (1978). Tammemagi and Chieslar (1985) compare the results of their review consisting of 160 data points to that of Annor and Jackson (1982). They concluded that Youngs modulus values for Pinawa granite examined in the latter review have a higher mean value than the mean obtained in their review. Tammemagi and Chieslar (1985) obtained a mean value of 54.9 GPa and a standard deviation of 18.9 GPa for their review. The Annor and Jackson values ranged from 55.9 to 74.0 GPa. Values of Poisson's ratio however were found to be in close agreement. Tammemagi and Chieslar (1983) reported a mean value of 0.235 and a standard deviation of 0.094 based on 121 samples. Annor and Jackson reported means of 0.22 to 0.28 for a variety of sample sizes.

The results of Tammemagi and Chieslar (1985) are summarised in Figures 3.2 and 3.3 in the form of frequency distributions for Modulus of Elasticity and Poisson Ratio. Additional representative values are presented in Appendix C.

Porosity

Porosity, due to its multiplicative effect in the storage coefficient, can be a significant source of variability. Although good reviews of porosity values are available in the literature for generic rock types, only sporadic measurements

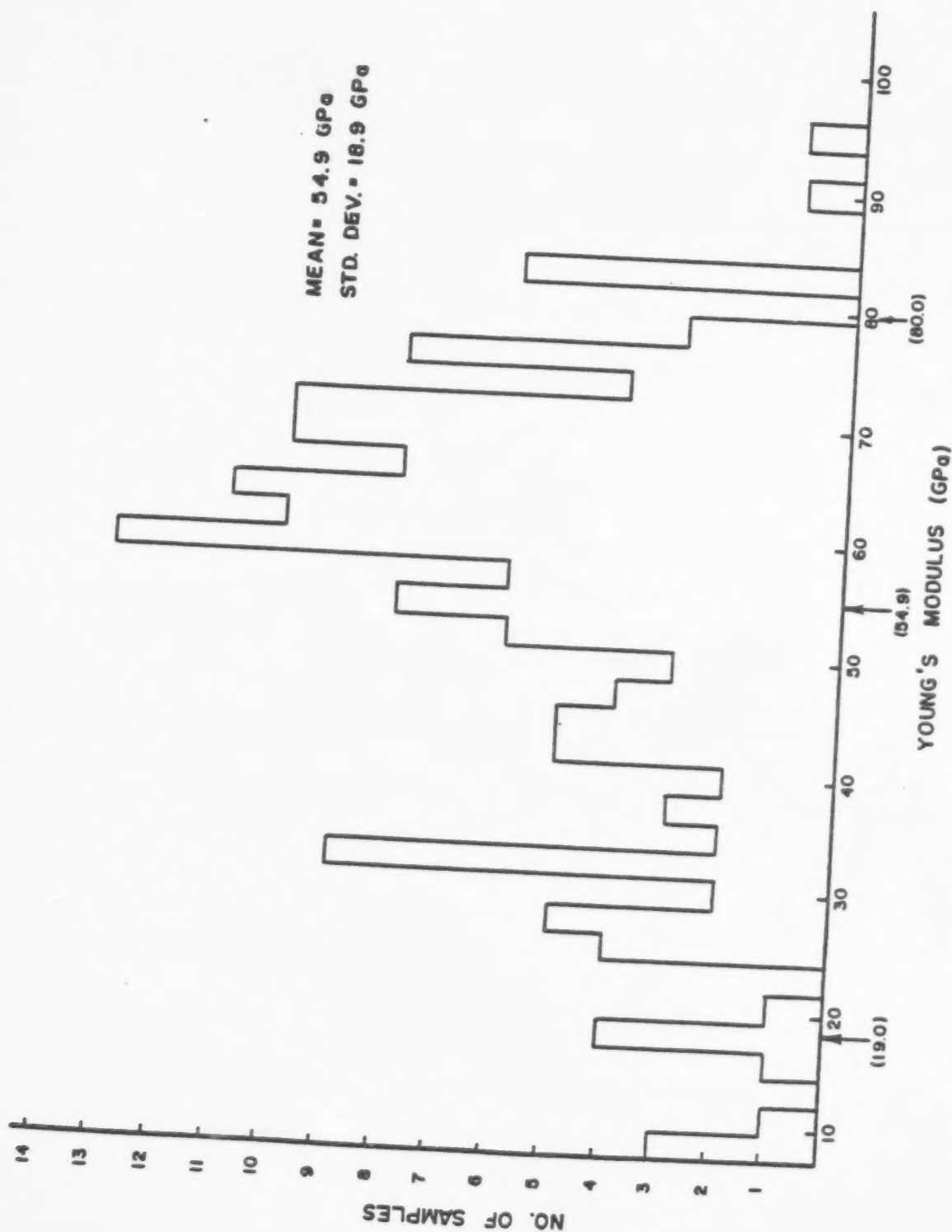


Figure 3.2 Frequency Histogram of Young's Modulus for Crystalline Rock (after Tammemagi and Chieslar, 1955)

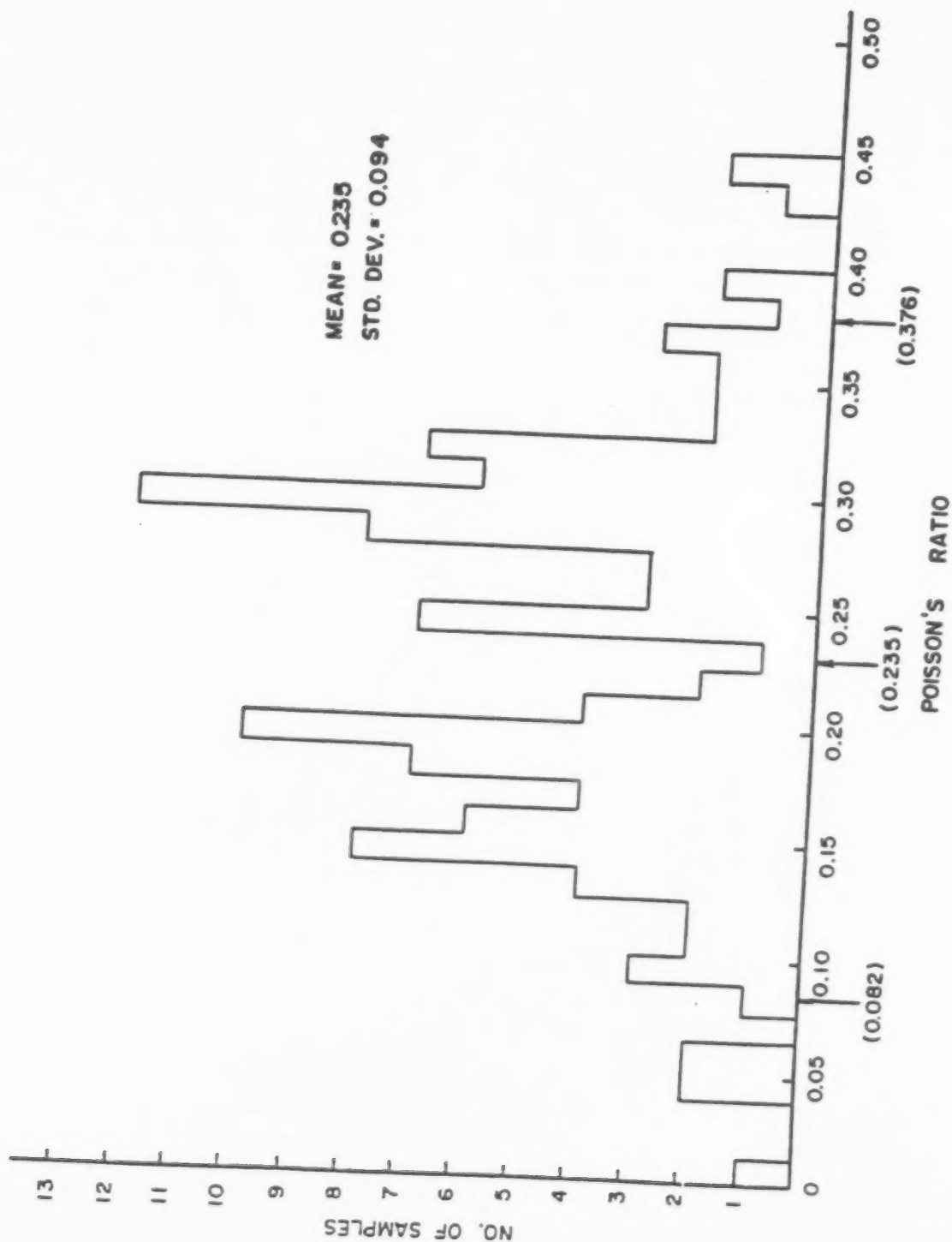


Figure 3.3 Frequency Histogram of Poisson's Ratio for Crystalline Rocks (after Tammemagi and Chieslar, 1985)

have been performed at most of the major research sites. The extent of these measurements are described in the following sections, while actual values have been included in Appendices C.1 through C.13.

It can generally be seen that bulk porosity measurements tend to be low, usually less than 1%, with the majority of such measurements being of the order of 0.1 to 0.8%, although values as high as 6% have been reported by Norton and Knapp (1977). Brace et al. (1982) consider four sources of porosity measurements in deriving the range of values presented in Figure 3.4. From this figure it could be inferred that matrix porosity values for granites tend to be higher than mafic rocks but lower than tuff values. The results of our review do not indicate any significant correlation between rock type and porosity values. Fracture and effective porosities being on the order of 10^{-4} are generally significantly lower than bulk (i.e., total) or matrix values.

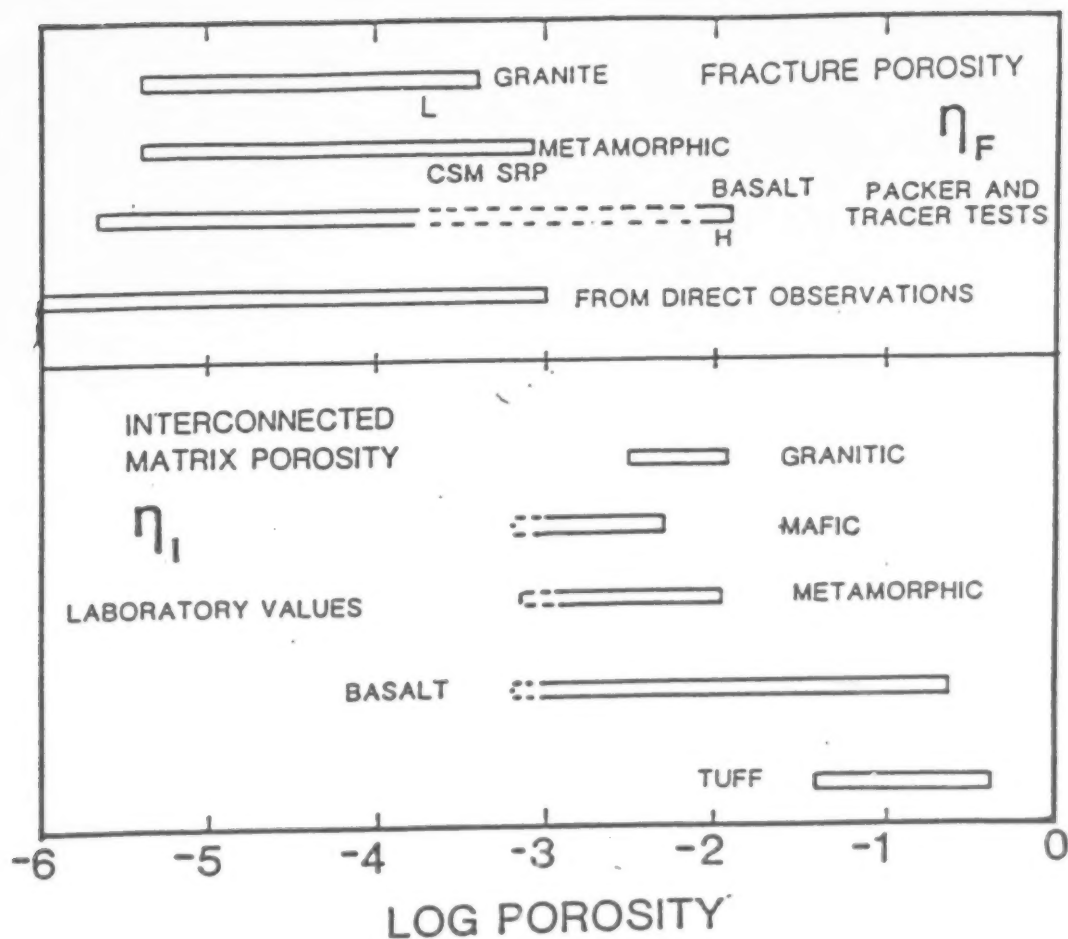


Figure 3.4 Ranges of Fracture and Matrix Porosity for Various Rock Types (after Brace et al., 1982)

4.0 FRACTURE CHARACTERISTICS

4.1 Definitions

In the past, a number of related and general terms have been used to describe breaks or discontinuities in plutonic rocks. This text will abide by the definitions outlined in International Society for Rock Mechanics (ISRM, 1978) with some minor modifications. The preferred term in this text is fracture to describe discontinuities in rocks. The following definitions apply (ISRM, 1978):

- Fracture - The general term for any mechanical discontinuity in a rock mass having zero or low tensile strength. It is the collective term to describe all breaks in a rock mass and includes most types of joints, weak bedding planes, weak schistosity planes, weakness zones and faults.
- Joint - A break of geological origin in the continuity of a body of rock along which there has been no visible displacement.
- Fault - A fracture or fracture zone along which there has been recognisable displacement from a few centimeters to a few kilometers in scale.

ISRM (1978) prefers to use discontinuity instead of fracture as the general term and it is conceded that this term is perhaps the more appropriate to describe all fractures; however, the more popular term in the literature is fracture. It should be noted that throughout the literature fracture, discontinuity, fissure joint and fault are often used interchangeably.

The primary fracture characteristics are defined by the following parameters (ISRM 1978):

- Orientation - Attitude of fracture in space. Described by the dip direction (strike or azimuth) and dip of the line of steepest declination in the plane of the fracture.
- Spacing - Perpendicular distance between adjacent fractures. Normally refers to the mean or modal spacing of fracture sets.
- Aperture - Perpendicular distance between adjacent rock walls of a fracture, in which the intervening space is air, water or infilling material.
- Length - Fracture trace length as observed in an exposure.

Parallel and similarly oriented fractures at a regular spacing form fracture sets. A number of sets may be found in the same rock mass and these combine to form a fracture system.

In addition, several secondary parameters are often used (but seldomly reported) to aid in the identification of fractures. These parameters include (ISRM, 1978):

- Roughness - Inherent surface roughness and waviness relative to the mean plane of a fracture.
- Infilling - Material that separates the adjacent rock walls of a fracture and that is usually weaker than the parent rock.
- Seepage - Water flow and free moisture visible in individual fractures or in the rock mass as a whole.

Fracture characteristics can therefore be described by careful study of the above parameters. The origins of fractures and the field methods used to describe each of the primary fracture parameters will be documented in the following sections. A general discussion of field measurement techniques for the secondary parameters is also given.

4.2 Origin of Rock Fractures

Natural fractures in rock depict the local state of stress at the time of fracturing and therefore the orientations, spacing and continuity are all determined by the mode of origin of the fracture system (Nelson, 1979). The purpose of this section is to provide a discussion of the various classifications of fracture systems as they relate to their origin.

Stearns and Friedman (1972) suggest that all fractures may be classified as either shear or extensive fractures. Extension fractures are created when tensile stress exceeds the tensile strength of the rock (Griggs and Handin, 1960). Such a condition will result in fractures occurring in a plane normal to the maximum tensile stress and displacement parallel to the maximum tensile stress. Shear fractures differ from extension fractures in that any displacement will occur parallel to the fracture surface.

Stearns and Friedman (1972) indicated that the geometry (i.e., orientation) of shear fractures is governed by both the shear strength as well as the internal friction of the rock. As a result shear fracture planes are not usually coincident with the planes of maximum shear stress (at 45° to the maximum principle stress direction) but will occur at some lesser angle.

Both naturally and experimentally created fractures can be classified as either shear or extension fractures. In natural systems, the stress state associated with fracture generation may be induced by a number of phenomena including tectonic events, contractional forces and glacial (or erosional) rebound.

- Tectonic Events

Both shear and extension fractures may be associated with specific geologic structures such as faults and folds. The trend of the fracture pattern is related to the structural trend and varies with changes in structure. Fractures associated with faults are generally attributable to the same stress state that caused the fault (Stearns and Friedman, 1972) and therefore the fracture orientations and extension fractures associated with the fault can be predicted from knowledge of the attitude of the fault. Fracture development caused by folding is considerably more complicated because any particular volume of rock can undergo several different stress states through its folding history. Stearns and Friedman (1972) identified five major fracture patterns associated with folds. Fractures caused by folds are a result of the folding process and not of the regional stress that initiated the folding. Upwarps, downwarps or flexing of lithospheric plates have also been identified as sources of regional fracture systems (Stearns and Friedman, 1972).

● Contractional Forces

Contractional Fractures usually occur as a result of:

- (1) desiccation - fracturing due to shrinkage caused by drying;
- (2) syneresis - fracturing due to dewatering;
- (3) thermal contraction - Fracturing caused by contraction as a hot rock cools (i.e., columnar jointing) or climate changes;
- (4) Mineral Phase-Change - Fracturing caused by stresses induced by volume reduction due to mineral phase changes.

This type of fracture is initiated by internal changes (body forces) and is not governed by tectonic influences.

● Rebound Forces

Fractures resulting from unloading, release of stored stress and strain, creation of free surfaces or unsupported boundaries and, in general, give rise to surface-related fractures. Erosional unloading can cause lithostatic stress relief and result in extension fractures forming parallel to the erosional surface. The sets of flat-lying fractures found in granitic rocks (commonly called spalling, sheeting or sheet structures) are formed in this manner. Similarly, rock bursts result from stress relief in quarries or mines.

In addition to the stress induced fractures identified by Stearns and Friedman, a number of other mechanisms may induce fractures. For example, mechanical and chemical weathering such as freeze-thaw cycles, small-scale collapse and subsidence, mineral alteration and diagenesis can give rise to fracture systems.

4.3 Methods for Determining Fracture Characteristics

Fracture characteristics can be determined by surface mapping, borehole logging and photogrammetric techniques. The primary information obtained using these methods describes the orientation, spacing, length and aperture of the fracture planes such that the fracture system and its continuity can be adequately described. The various methods are, in general, capable of determining all of the fracture characteristics described in Section 4.1.

4.3.1 Surface Mapping

The most common method of measuring the spacing, length, aperture and orientation of surface fractures is outcrop mapping using a survey line (Terzaghi 1965; Piteau, 1971; Call et al., 1976). The survey line consists of a measuring tape placed across an outcrop such that it intersects the greatest number of fractures. The measuring tape becomes a reference line with a known orientation with all fractures that intersect the reference line being recorded. In practice, the measured area usually extends one to two meters above and below the line but may be enlarged or reduced depending on the number of fractures encountered.

To determine the orientation or attitude of the fractures intersecting the reference line, the strike and dip of each fracture is measured using a compass and clinometer. The strike is the horizontal direction of the fracture plane while the dip is the maximum angle between the horizontal and the fracture plane. The orientation data (strike and dip) is recorded on a data sheet.

Fracture spacing is estimated from the average distance between fractures of the same set. Data reduction and statistical analysis is often required to identify the mean spacing for each set.

Fracture length is recorded as the observed trace length in the outcrop and it is assumed that the fracture is at least as long as its trace. Fracture lengths that appear to extend beyond the edge of the outcrop are noted as such. The termination of fracture length is also noted with regards to type (e.g., unobservable, single end, double end, termination at another fracture, etc.).

Fracture aperture is measured as the perpendicular distance between the two fracture walls. An indication of the nature of the aperture (e.g., open, closed, filled) is recorded. Apertures recorded at outcrops will be affected by weathering and may not be representative of apertures within the rock mass (i.e., borehole, mine or quarry excavations). Descriptions of aperture filling materials and fracture surface roughness is also noted.

Survey line and fracture characteristic data typically recorded include:

- Bearing and plunge of the reference line;
- Dip direction and face angle of the rock exposure;
- Line number, elevation and location;
- Fracture strike and dip;
- Distance along the tape where the fractures intersect;
- Rock types and structure type (e.g., fracture, fault, shear zone, etc.);
- Length measured as the maximum traceable distance;

- Roughness of fracture wall or surface (e.g., smooth or rough);
- Aperture of fracture measured perpendicular to fracture plane and indication of openness;
- Filling materials including type and thickness;
- Water conditions (e.g., flowing, dry, etc.).

The additional data collected is used to fully describe the fracture characteristics.

Other survey lines oriented to intersect the first survey line provide complete coverage of the outcrop. Additional survey lines are required to compensate for fractures parallel to the initial line.

4.3.2 Oriented Core Logging

The orientation of fractures within a rock mass can be determined using oriented core logging techniques. In places where outcrop is unavailable, core logging may be the only means of assessing the rock quality. A number of methods exist to orient core ranging from simple to sophisticated techniques.

The photographic method requires the use of a borehole camera that is lowered down the borehole to record the hole orientation with respect to some reference on the top of the core. In this method, the entire core is scribed with a reference line inside a special core barrel (e.g., Christensen-Hiigel Barrel and B.H.P. orienting barrel). The top piece of core is then oriented according to the reference line and the camera reference and the remainder of the core is oriented relative to the top piece. A similar technique simply obtains

an oriented imprint, using modeling clay, of the top of the core run and the remainder of the core is oriented in reference to the top piece.

The mechanical method, used only in inclined holes, utilizes the Craelius Core Orientor. This technique consists of two imprinting methods: a ball bearing that imprints the bottom side of a soft metal plate; and metal pins at the front of the instrument that take an imprint of the top piece of core. By matching the pins to the first piece of core and the bottom imprint of the metal plate the core can be oriented in reference to the inclined borehole.

Another technique, for inclined holes only, uses a vial of paint that is broken on the top of the core. The paint dribbles down the lower side of the core thus marking it in reference to the inclined hole.

Once the core is sufficiently oriented (the above methods are usually successful in orienting 75 - 100% of the core) the fractures can be measured in terms of their strike and dip. The logging of oriented core can be conducted in a manner similar to the outcrop mapping-survey line method with the borehole representing the reference line.

Qualitative estimates of aperture can be provided from the original reconstructed core while spacing is determined from the mean distance between fractures within one set. Fracture lengths cannot be determined from core logging but with few exceptions, the remainder of the fracture characteristics can be described using this method. Additional core characteristics such as rock type, core recovery, rock quality designation (RQD), and others are included in the core logging data.

Core logging has a similar limitation as the survey line method in that it will not detect fractures that are parallel to the borehole. For example a vertical borehole is unlikely to intersect a significant number of vertical or steeply-dipping fractures. In order to obtain the most fracture related information from a single borehole, inclined holes should be drilled at angles normal to the dominant fracture sets (as determined from outcrop mapping).

4.3.3 Borehole Geophysical Logging

A wide range of geophysical techniques have been used in investigations of fractured rock but only a few methods are suitable for identifying detailed fracture characteristics other than fracture locations. Geophysical logging techniques suitable for identifying fracture locations/spacings, orientation and apertures include:

- Borehole television logs
- Acoustic televiewer logs
- Caliper logs
- Tube wave logs

Other logging techniques have been used in fracture surveys (i.e., neutron, gamma-gamma, resistivity, acoustic, temperature, heat pulse flowmeter, spinner flow meter) but primarily yield only a location or depth with no information on the orientation or aperture (open or closed).

Much of what is described below regarding geophysical logging techniques and applications is taken from an excellent review by Earth Technology Corporation (1985b).

4.3.3.1 Borehole Television Logs

Borehole television logs consist of recording a picture of the borehole using a down-hole camera. The camera consists of a two way mirror for forward and side scanning, a compass for determining orientation and lamps for illuminating the borehole wall (Lau, 1980). Video signals from the camera are transmitted to surface via a cable and are stored by a videotape recorder. The same cable controls the camera and provides operational power.

The borehole camera provides geologic mapping capabilities and information on fracture type, orientation, aperture, depth and character (Earth Technology Corp. 1985b). Orientation is determined by measuring the depth and strike of the highest and lowest point on a fracture plane which appears as a sinusoidal curve on the borehole wall. The dip angle is estimated from the measurements of the high-to-low-point distance (h) of the fracture plane and the borehole diameter (d) such that (Lau, 1980):

$$\text{Dip Angle} = \tan^{-1} \frac{h}{d}$$

If the borehole is vertical the strike and dip are true strike and dip but if the borehole is inclined the strike and dip are apparent and must be corrected (e.g., using spherical trigonometry) to obtain true values.

The fracture aperture is measured from the midpoint of the sinusoid and Earth Technology Corp. (1985b) reported that apertures as low as 0.1 mm are detectable. Fracture locations are reported on data sheets as well as the videotape so that fracture spacing/frequency logs are

produced. The TV camera is also useful for orienting core as described previously.

4.3.3.2 Acoustic Televier Logs

An acoustic televier records images of fractures by reflecting acoustic energy off the borehole wall and measuring the change in intensity of the returning signal. The intensity changes each time the acoustic energy crosses a fracture. The return signal is monitored on an oscilloscope and a camera attached to the oscilloscope provides pictures of the acoustic response. As the probe moves uphole, these pictures provide a continuous log of the borehole. The acoustic televier covers 360° of the borehole and thus the logs represent the borehole as split vertically along magnetic north and laid out horizontally. As in the TV log, the fracture planes appear as sinusoidal curves and the method of determining the true strike and dip are therefore similar.

Acoustic televiers have been used to identify fracture locations, apertures and orientations with a high degree of accuracy but is adversely affected by changes in borehole diameter or rifling on the borehole wall.

4.3.3.3 Caliper Logs

Caliper tools consist of one, two, three or four arms which respond to changes in borehole size and provide a direct measurement of the borehole diameter. Fractures appear on the logs as larger diameter intervals and, if a three or four arm tool is used, the depth of response of each arm can be used to determine the apparent or true dip of the

fracture. The fracture aperture can also be estimated from caliper logs but it has been noted by Davison et al. (1982b) that the fracture edge tends to break away during drilling yielding a greater than true fracture width.

Caliper logs are useful in determining fracture location, aperture and dip but, unless the tool is oriented, does not provide a strike.

4.3.3.4 Tube Wave Logs

Tube waves are high-amplitude, low-velocity impulses generated by the transfer of compressional waves (caused by a surface explosion) from the surrounding rock body onto fluid-filled fracture zones intersecting the borehole (Huang and Hunter, 1984). The position and amplitude of the tube waves have been used to identify open fractures having an aperture down to a small fraction of a millimeter and to provide an indication of hydraulic conductivity. The tube wave method does not provide fracture information other than location and relative apertures but is considered important because of its potential to sample large areas (up to 8 to 15 m) surrounding the borehole.

4.3.4 Photogrammetry

Large scale fracture, fault and lineament characteristics may be best estimated through the use of photogrammetric techniques. In this method, air or ground photographs are used to examine large or inaccessible areas.

Air photographs are commonly used as the first approach in the description of the fracture characteristics of a region.

Because of their large coverage, air photos will detect large scale discontinuities such as faults, shear zones, lineaments, geologic contacts, etc. The strike of these features can be easily determined by comparison to a north arrow set on the air photo. Trends of large scale lineaments tend to reflect regional fracture systems. Comparisons between length versus strike-orientation can be used to determine major fracture sets. Air photo lineament density maps can also be produced by this method.

To a lesser degree, ground photographs can be used to map the orientation of numerous fractures in rock faces or cliffs. The method consists of taking photographs of the rock face from suitable vantage points, determining a reference control line or a number of known reference points for orientation and distance markers and then using the photographs to measure and record fracture orientations. This method is best suited to areas that are inaccessible or that are uneconomical (due to a large number of fractures), to measure using the survey line method.

4.4 Presentation of Fracture Characteristics

Fracture characteristics, described in the literature, are presented in a variety of different manners. This section briefly presents the more common or the most descriptive methods together with examples of each. Presentation techniques include:

- Block Diagrams (Figure 4.1) - A three dimensional perspective drawing drawn to scale and oriented with respect to true north used to present fracture orientation and spacing data.

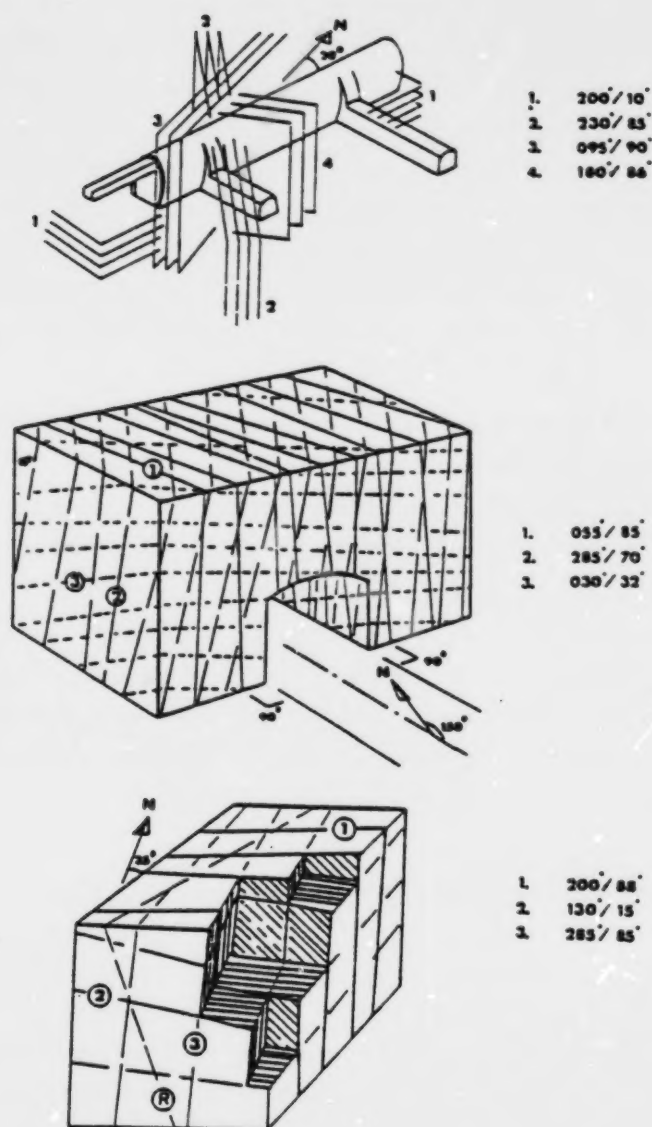


Figure 4.1

Examples of perspective views and block diagram for illustrating fracture orientations (ISRM, 1978)

- Rose Diagrams (Figure 4.2) - A compass rose marked from 0 to 360° with radial lines in 10° increments and numbered concentric circles representing the number of observations along the radii. This diagram is used to present orientation (strike) data.
- Spherical Projections (Figure 4.3) - Fracture planes oriented in space through a common centre point extended to intersect the lower half of a sphere such that the trace on the surface of the sphere represents the orientation of the plane. The lower hemisphere is an equal area or equal angle projection and the fracture plane an arc scribed inside the hemisphere. By projecting this information onto the circle formed by the lower hemisphere, one obtains an equal area net. An alternate method known as polar diagrams can also be used. In this method the intersection of normals (poles) with the centre point of the plane are plotted onto the projection resulting in the fracture plane represented by a single pole. Spherical projection methods (such as equal area nets or polar diagrams) are used to display orientation data.
- Frequency Histograms (Figure 4.4) - A histogram of fracture frequency versus fracture strike, dip, spacing or length or depth below surface.
- Frequency Contour Diagrams (Figure 4.5) - A contoured plan view of fracture frequency for a region (i.e., contoured frequency represents the number of fractures in 1% of total area).

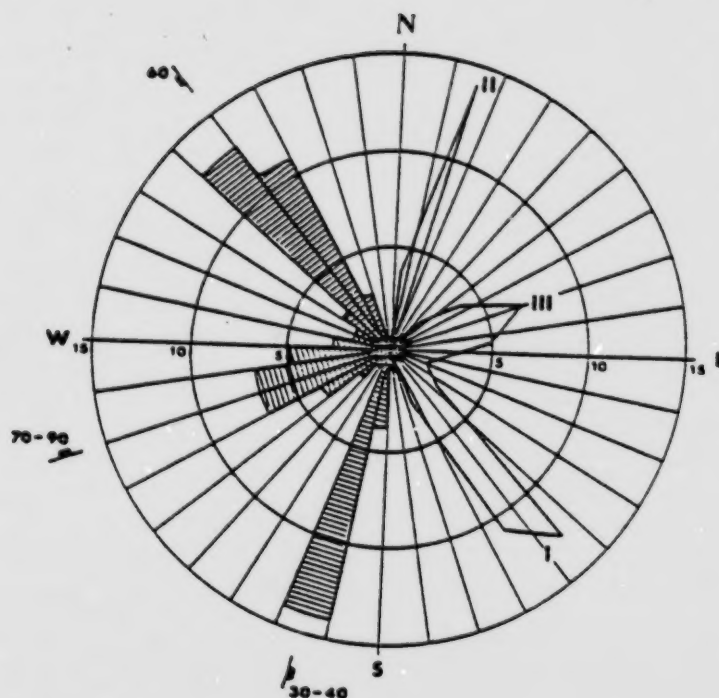


Figure 4.2

Two methods of representing fracture
orientation data on a joint rosette
(ISRM, 1978)

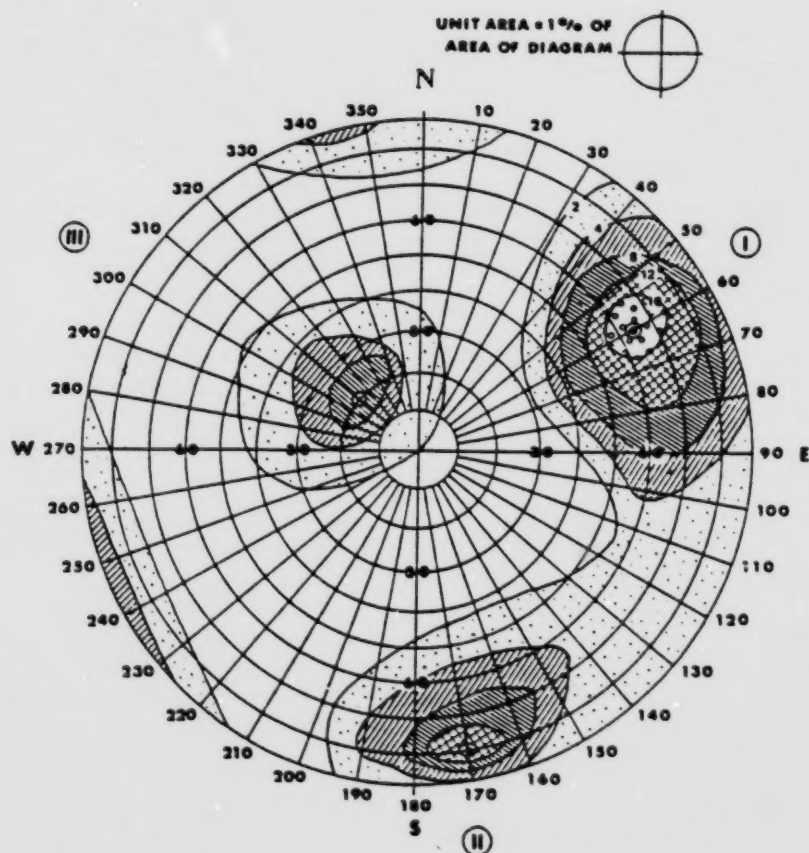


Figure 4.3

Example of an equal-area polar diagram illustrating the orientation of three fracture sets (ISRM, 1978)

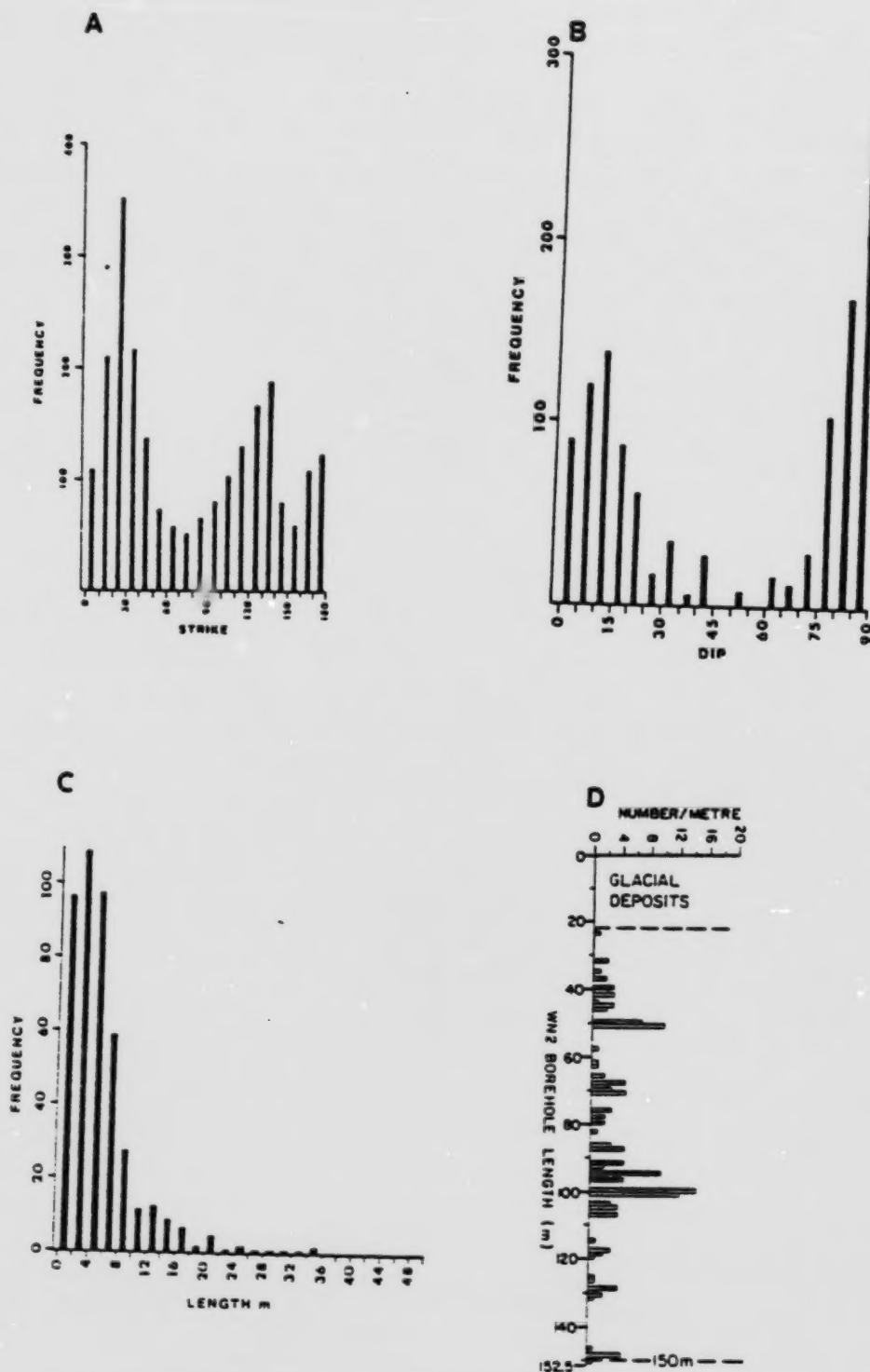


Figure 4.4

Examples of frequency histograms (A) Frequency versus strike (B) Frequency versus dip (C) Frequency versus length and (D) Frequency versus depth

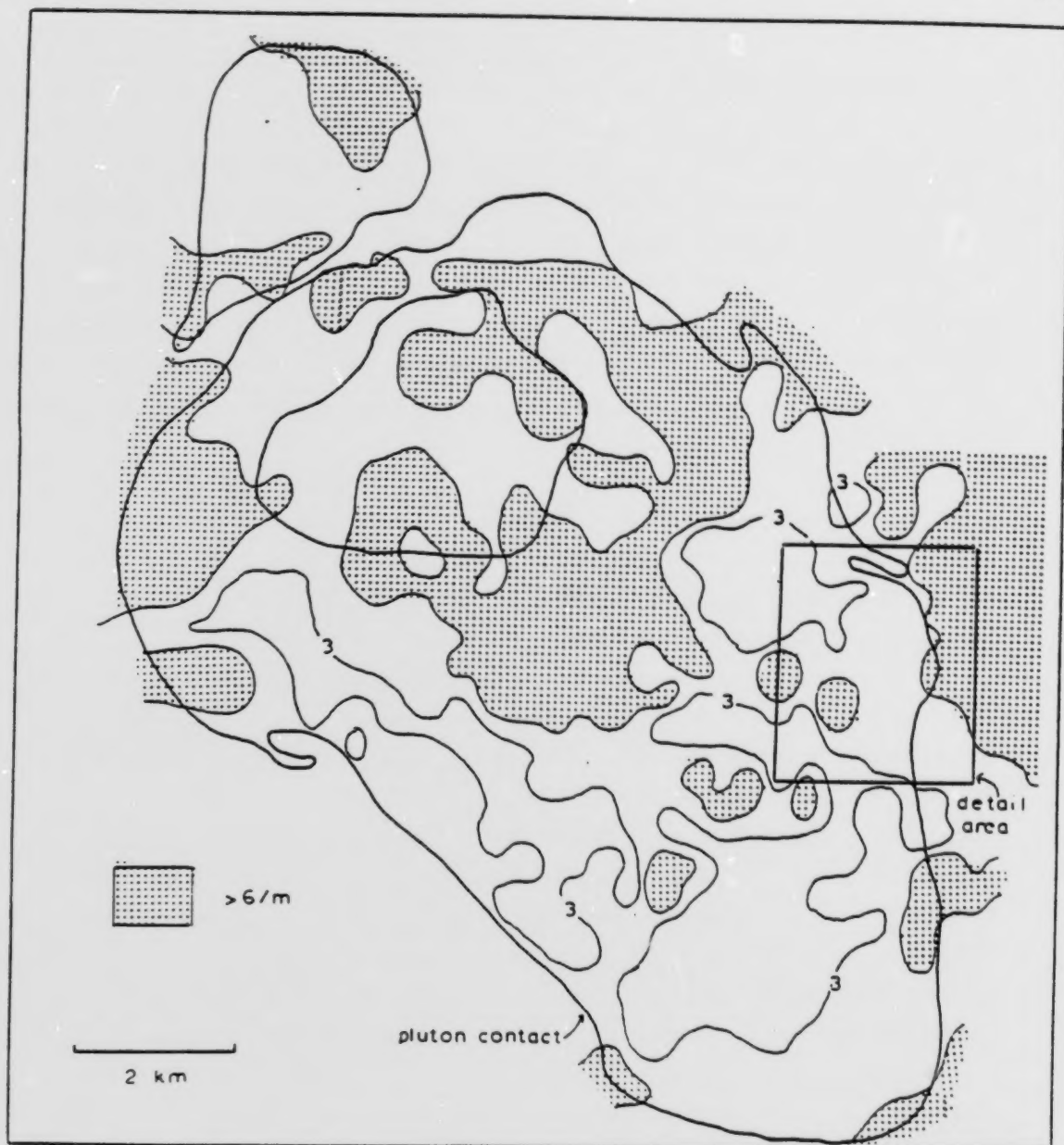


Figure 4.5

Example of total fracture frequency contour plot for a regional area. Contours are in number of fractures per metre times three (Stone, 1980)

4.5 Accuracies and Uncertainties in Measurements of Fracture Characteristics

The purpose of determining fracture characteristics is to completely describe the fracture systems contained within a rock mass. To this end, sampling techniques such as those described previously are used but, like most sampling methods, there are a number of inherent uncertainties that may affect the accuracy or confidence level of the results. This section will describe some of the uncertainties and attempt to examine the accuracy of the various measurement techniques.

The primary objective of a sampling technique is to draw conclusions about the characteristics of a group of data by analyzing the characteristics of a small sampling of the group. In determining the characteristics of fractures in a rock mass, it is not feasible to measure every fracture and therefore small subsets of the entire population are sampled in order to draw conclusions about the population as a whole. The sampling of fractures is hindered by the fact that fracture mapping is not entirely random but is dependent on the availability or accessibility of outcrops or the angle of inclination of boreholes (which may or may not be expressly for fracture mapping purposes). Outcrops tend to represent the less fractured areas of the rock mass simply because weathering and erosion will deteriorate less competent parts of the rock (i.e., surface expressions of faults or shear zones are typically at lower elevations than the intact rock and therefore are more likely to be covered by overburden). Outcrops are usually positioned parallel to the structural trend (e.g., strike of a fault or axis of a fold) of the rock mass or parallel to the advance or retreat of glaciers. The location of an outcrop or a borehole within the geologic setting may also limit surface mapping as a method of sampling the entire population. For example, locations near a fault, shear zone, fold belt, or pluton boundary may yield a larger number of fractures in a fracture set than may be found in

the rock mass as a whole. The sampling of an individual outcrop, therefore, may not represent a suitable sample of the entire population.

Terzaghi (1965) found that blind spots exist in survey line mapping. The blind spots are found parallel to the survey line and parallel to the outcrop surface. Fractures in these directions will be overlooked or sampled to a lesser extent than those at angles to the survey line. Similar blind spots exist in fracture mapping of boreholes, mines or tunnels. In these cases the fracture orientation (strike and dip) and spacing must be taken into consideration with respect to the orientation and length of the borehole, mine or tunnel.

Surface mapping is also limited by the size of the outcrop in that complete fracture surfaces may undulate at a scale larger than the size of the outcrop (Piteau, 1973). Small scale irregularities similarly may result in errors of, typically, 10° for strike measurements and 5° for dip measurements (Piteau, 1973).

Earth Technology Corp. (1985a) report that the above mentioned uncertainties can be reduced and accuracy of measurement increased by:

1. correcting for the effects of non-random orientation of exposed rock surfaces;
2. making observations in an adequate number of appropriately oriented survey lines; and
3. plotting the results of the survey on polar diagrams that are corrected for the effect of the angle of

intersection between the joints and the exposed rock faces (Terzaghi, 1965).

Robertson (1970) has suggested that 100 measurements per fracture set are necessary to obtain 95 percent confidence to within ± 20 percent of the true value. Observations of this number are rarely achieved in practice and the number of observations required often depends on the fracture frequency, spacing and number of sets.

Priest and Hudson (1976) found that to estimate the number of continuities per metre to within a reasonable precision, a scanline length at least 50 times the mean discontinuity spacing is required and that at least 200 measurement values were required to describe the distribution of the spacing (negative exponential distribution). Priest and Hudson (1981) found that fracture spacings (x) typically follow a negative exponential distribution of the form:

$$f(x) = \lambda e^{-\lambda x}$$

where λ is the average number of discontinuities per unit length. It follows that the mean and standard deviation of the fracture spacing is equal to $1/\lambda$. The confidence level and the error bandwidth are then dependent on the sample size and can be used to determine the appropriate number of samples to obtain a specific confidence level. Fracture lengths have also been found to conform to the same distribution known as a Poisson distribution (Priest and Hudson, 1981).

Uncertainty in the measurement of fracture lengths often exists because the fracture may extend beyond the area of observation (i.e., beyond the outcrop) resulting in an incompletely measured (censored) length. Those fractures with long fracture lengths

are also more likely to intersect the survey line than those that are shorter. On the other hand, very short fractures are difficult to measure accurately. Priest and Hudson (1981) suggest that it is feasible to observe and measure trace lengths as low as 10 mm both in the field and from photographs. Fractures shorter than this length will not seriously affect the data. The precision of the estimate of mean trace length can be determined by the same technique given for mean spacing if the fracture lengths follow a negative exponential distribution (Priest and Hudson, 1981) and therefore the accuracy is dependent on the number of measurements. By defining the relationships between complete length, trace lengths intersected by a scan line, semi-trace length (one end of trace length) and censored semi-trace length (both ends hidden), Priest and Hudson (1981) developed graphical and analytical methods of estimating mean fracture length from censored outcrop measurements.

Fracture aperture measurements and characterization are difficult to achieve in a field setting. Apertures vary from zero (closed) to some maximum value depending on the nature of contact between the rock walls and the position along the fracture. Typically the fracture aperture width is affected by the variability of wall roughness and infilling material. In order to accurately define the mean aperture width the roughness and infilling material must be quantified. Although the percentage of infilling material can be estimated to a reasonable degree, the wall roughness is often qualitative and subjective (Call et al., 1976; ISRM, 1981). Outcrop measurements of apertures are affected by stress relief, weathering and blast damage which tend to exaggerate the true aperture width in the subsurface (Evans, 1983; Price 1979). Similarly borehole measurements of apertures may be affected by drilling damage (Davison et al., 1982b). In boreholes the aperture is measured over a small fraction of the

fracture length and in most cases is not representative of the mean fracture aperture.

The accuracy of direct measurements of apertures is dependent on the method used. Large apertures can be measured with a caliper gauge while narrower apertures can be accurately measured with a feeler gauge (Evans, 1983). Snow (1969) and Bianchi and Snow (1969) have developed a very accurate method of aperture measurement by using a fluorescent penetrant dye inserted into the fracture and enlarged photographs. The method results in an absolute error of about 0.0003 mm. Borehole television cameras and acoustic televiwers will detect fracture apertures to as low as 0.1 mm under ideal conditions.

Indirect measurement of apertures from borehole hydraulic tests depend upon some physical relationship between the quantity being measured (i.e., flow rate or hydraulic conductivity and the parameter of interest (aperture). These indirect measurements tend to provide equivalent single apertures based on the analogy of flow between smooth parallel plates. Equivalent single apertures calculated from hydraulic tests are not exactly comparable to actual fracture apertures due to channeling and roughness on the fracture wall or the presence of several contributing fractures.

4.6 Scale Considerations

Previous discussions of scale considerations have started with the concept of a representative elemental volume (REV) and this is appropriate for discussions of fracture characteristics. However, REV for fracture characteristics is difficult if not impossible to define. It has been mentioned previously that fractures originate from stresses induced by a number of

phenomena (tectonic, contractional, etc.) and a particular rock mass may be affected in different areas at different geologic times by several of these processes.

The resultant systems of fractures are therefore not randomly distributed but extremely variable in space and dependent on the direction of measurement. The appropriate scale at which to measure an REV is unknown but for fracture characteristics in general, measurement scales are usually dependent on the specifics of the investigation.

Common scales of measurement for fracture characteristics vary from regional investigations covering many square kilometres to microcrack studies of thin sections from cores. The scales of measurement can be grouped under the following categories:

- Regional Area;
- Detail Area;
- Grid Area;
- Borehole Length.

Borehole length is considered as a separate category even though it often spans several of the other scales because borehole fracture data represent a large portion of available information.

Regional fracture characteristics represent the largest scale of measurement and often include areas of 10's of square kilometres. Total area of the region can be defined by geologic (e.g., pluton edge), topographic (e.g., rivers, lakes, mountain ranges) or ownership boundaries. Defined areas are surveyed at large scales using air photographs, topographic maps, or reconnaissance mapping. Major structural trends such as faults, lineaments,

folds, geologic contacts are recorded based on easily accessible outcrops. The emphasis at the regional scale is to obtain general information regarding the major fracture systems for a large area. Data station density is usually relatively low.

Detail areas are at a smaller scale than the regional area. Boundaries may be defined by research or site boundaries, areas of particular interest, high outcrop densities or random subsets of the regional area. Surveys for the detail area would include mapping of all outcrop in the area for fracture characteristic using several survey lines per outcrop. Data station density would increase from that of the regional area.

Grid areas provide the smallest scale of fracture measurement. In this case, an area covering 10's of square metres is mapped in great detail. Surface cover is usually removed to expose the entire area and fractures are mapped at regular spacings using a grid pattern. Fracture characteristics are recorded along each line of the grid as in the survey line method. The grid area has the highest data station density.

Borehole length is worthy of mention in this discussion of scale because it provides the subsurface characterization of fracture patterns. Boreholes are commonly situated within or near the grid area to provide correlation to the surface mapping but may extend to several kilometers in depth. Shallow boreholes (i.e., less than 100 m) provide information on a detail or grid area scale. Deep boreholes (100 to greater than 1000 m) tend to reflect regional fracture systems or changes from the near surface.

5.0 SITE SPECIFIC VALUES

5.1 Stripa

5.1.1 Site Description

The Stripa site is located in south-central Sweden (see Figure 5.1) in an abandoned iron ore mine. The mine has facilitated access to and testing of a deep granitic rock mass as part of a site evaluation for a nuclear waste repository. Experiments underway at Stripa are part of a joint Swedish-American program in which the lead organizations are Karnbranslesakerhet (KBS, Nuclear Fuel Safety Program) for Sweden and Lawrence Berkeley Laboratory (LBL) under the Office of Nuclear Waste Isolation, United States Department of Energy (USDOE). The Swedish Geological Survey is also extensively involved in geologic and hydrogeologic programs at the Stripa site.

Geologically, the iron ore body is located within a synclinal trough which plunges approximately 20° to the east-northeast (Thorpe, 1979). Thermal and hydrologic experiments have been conducted in excavations mined into the granitic rock mass adjacent to the north limb of the syncline. The contact between the two rock types is quite irregular but has been observed to strike to the east-northeast and dip steeply to the southeast. The granitic rock mass, where the hydrologic experiments were conducted, is considered to be connected to one of several post-orogenic Precambrian plutons in the area (Thorpe, 1979). Olkiewicz et al. (1979) provide a detailed discussion of the area geology.

Hydrogeologic experiments/measurements have been ongoing since the late 1970's and consist of experiments at various scales

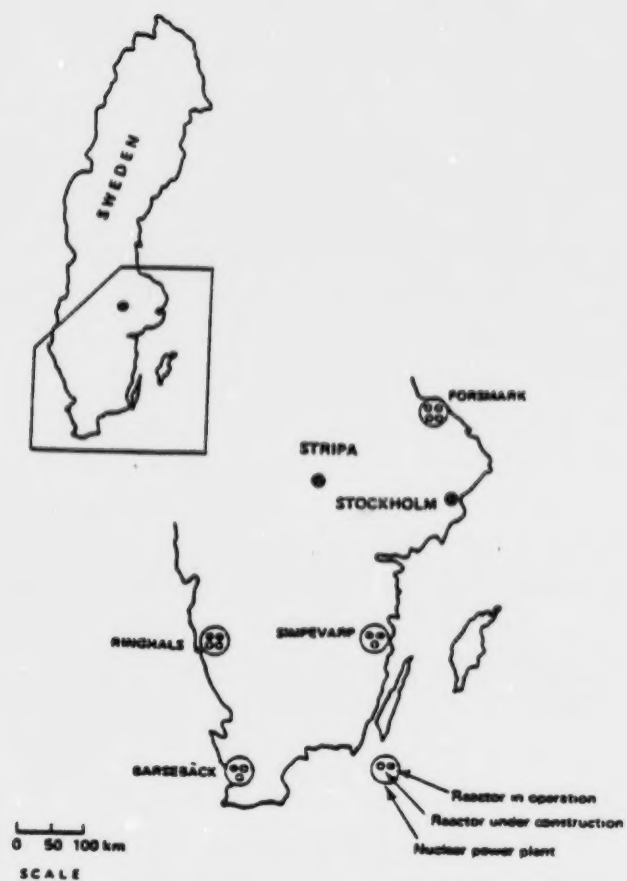


Figure 5.1

Location of the Stripa Mine, Sweden (after Olkiewicz et al., 1979)

ranging from lab analysis of cores to in situ macropermeability tests involving the hydraulic response of large rock masses. Boreholes have been drilled both from ground surface and in the subsurface. A brief description of these boreholes is as follows:

Surface Boreholes

WT-1 to WT-7 (Gale et al., 1979)

- water table wells
- WT-4 to WT-7 are all vertical wells located based on orientation of major fracture sets and separated by 15 to 30 m
- located approximately 100 m north of test facility
- WT-4 to WT-6 are 50 m deep and WT-7 is 100 m deep

SBH-1

- open borehole of 385 m length, 290 m deep, 76 mm diameter (diamond cored)
- inclined at 45° west-southwest (see Figure 5.2)
- borehole passes over top of underground test excavations

SHB-2

- diamond cored
- 82° inclined at 52° to the east-southeast
- 365 m long and 290 m deep (see Figure 5.2)

SBH-3

- 315 m long, 290 m deep (see Figure 5.2)
- inclined at 50° to the south

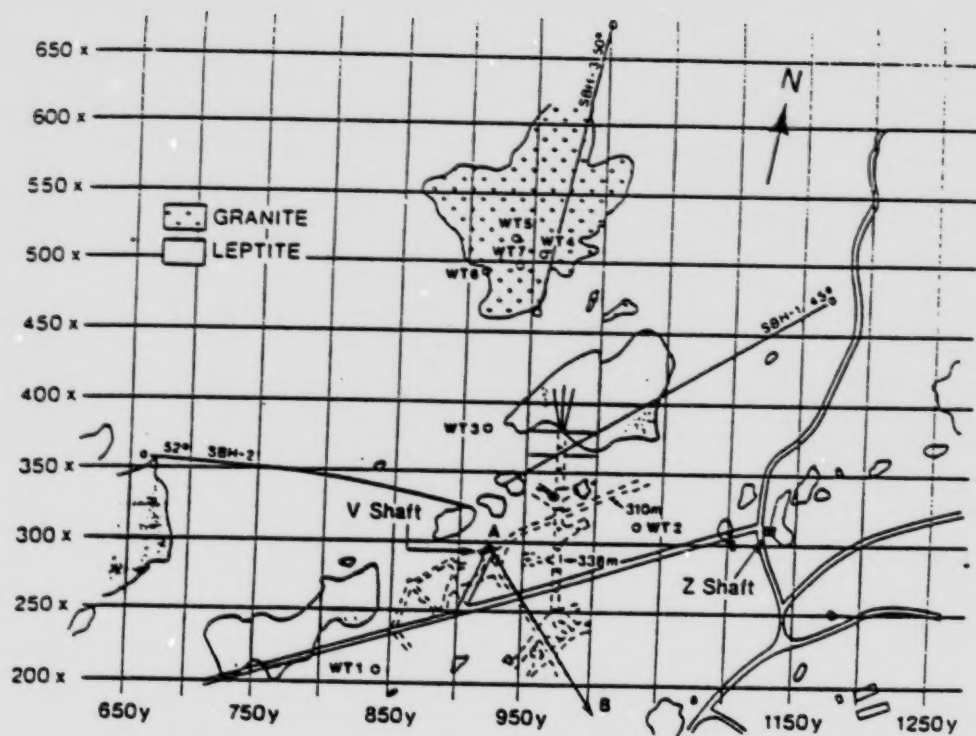


Figure 5.2 General Geology and Hydrology Borehole Locations, Stripa Mine (squares are 50 meters on a side) (Gale, 1981)

Subsurface Boreholes

R-series and H-series (Gale et al., 1979)

- located in north end of test excavations
- diamond cored, 30 m long, 76 mm diameter except R-1 and R-6 at 40 m in length (see Figures 5.3, 5.4)
- drilled at 360 m deep level

DBH2 (Olkiewicz et al., 1978; 1979)

- drilled at 338 m level
- horizontal hole at approximately 1.2 m above tunnel floor parallel to east tunnel wall
- originally 100.80 m long but partially removed during installation of tunnel which parallels borehole
- 45 m long tunnel driven parallel to borehole

DBH1 (Olkiewicz et al., 1978; 1979)

- drilled at 338 m level
- parallel to east wall of upper tunnel

DBHV1 (Olkiewicz et al., 1978; 1979)

- drilled at 410 m level
- vertical hole of 56 mm diameter, 471.4 m long

Test places 1 to 4 (individual borehole designations not available) (Lundstrom and Stille, 1978)

- drilled at 360 m level
- initially vertical boreholes drilled to 15 m depth, 76 mm diameter

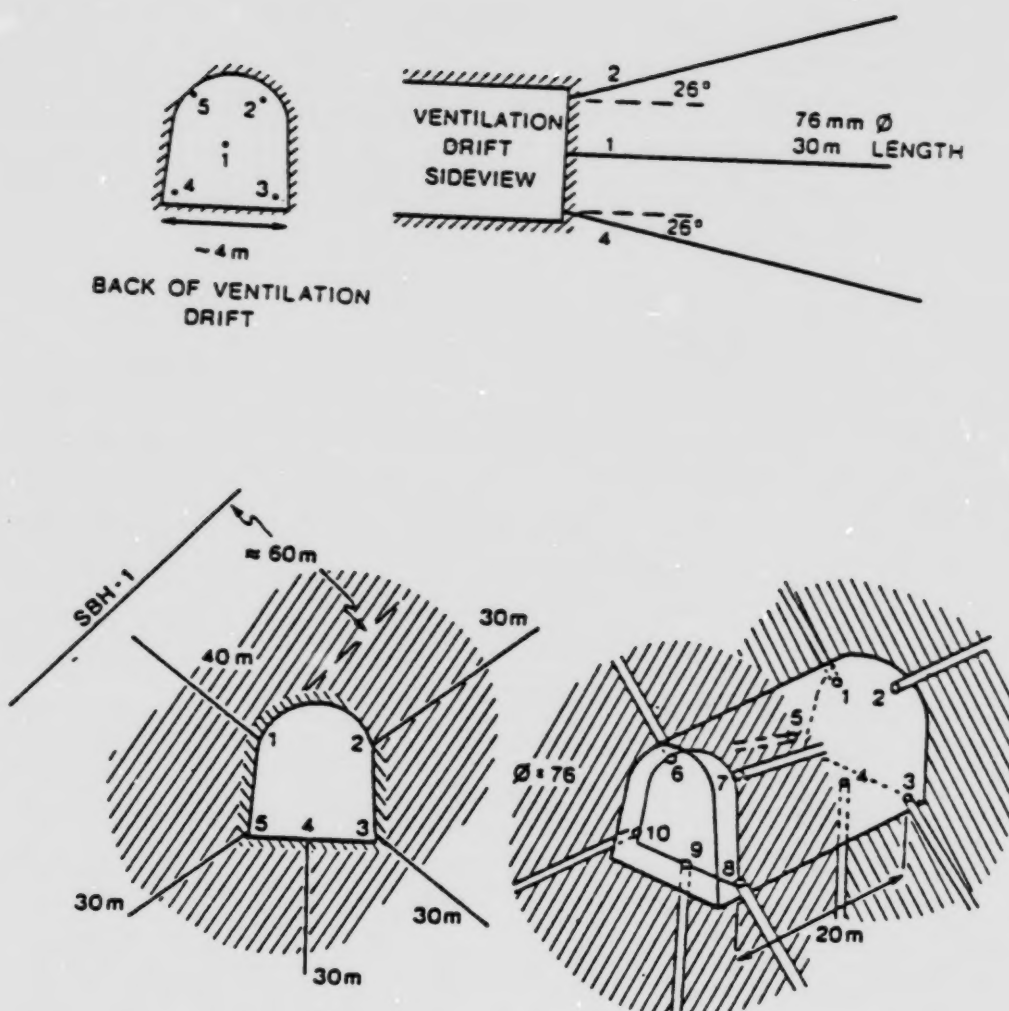


Figure 5.3

Location and Orientation of Subsurface Hydrology Boreholes, Stripa Mine (after Gale, 1981)

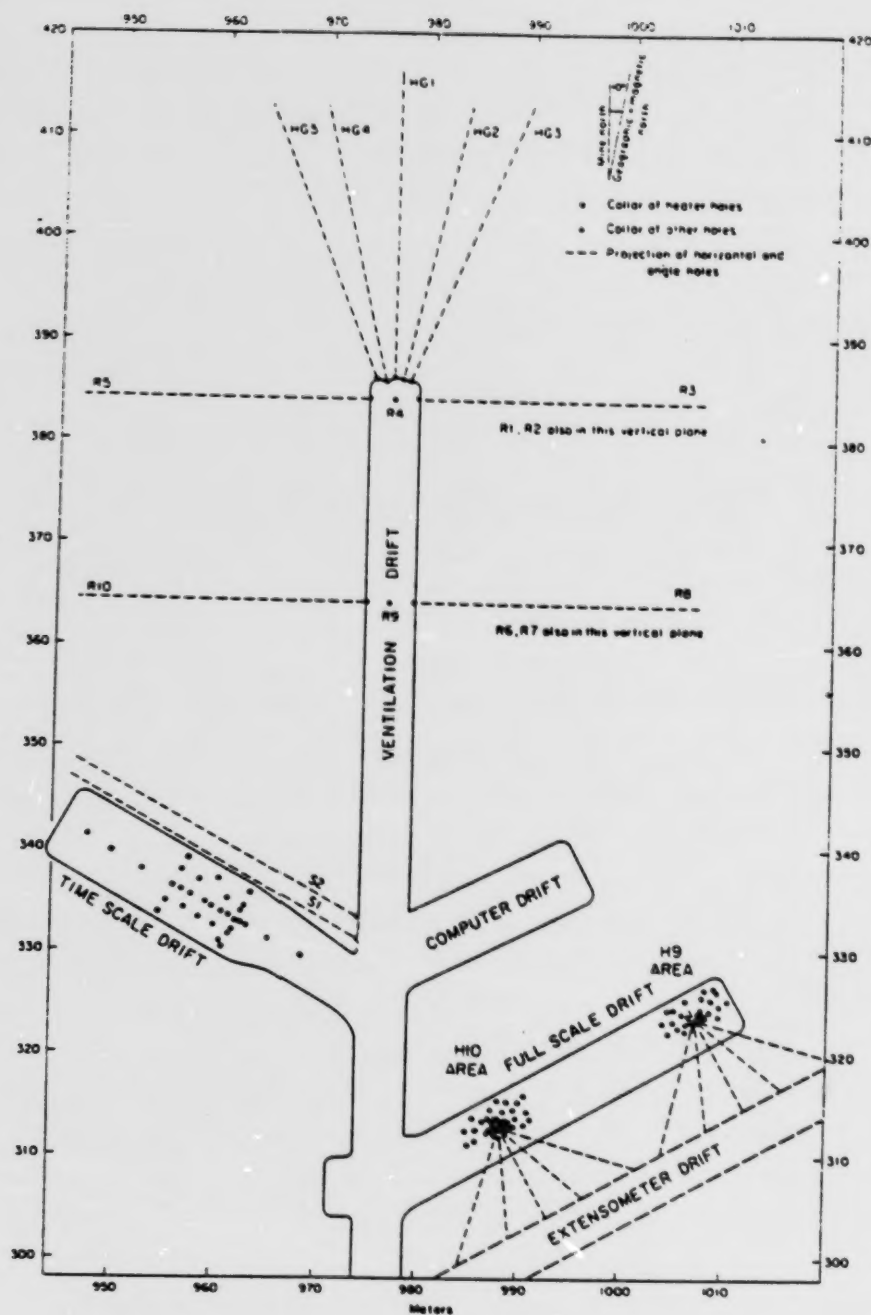


Figure 5.4

Plan View of Experimental Areas at the 340 M Level
Showing Subsurface Boreholes, Stripa Mine (after
Gale, 1981)

- at each of two test sites, 16 boreholes (76 mm diameter) were drilled around the circumference of a 3 m diameter circle to a depth of 10 m as well as central hole of 300 mm diameter

Geologic logs of core, distributions of major fracture zones, rock quality data (RQD) and formation pressures are available for much of the site and are reproduced in Appendix A.1 where relevant to the scope of this study.

5.1.2 Permeability

Hydraulic testing of the Stripa granites has been conducted by a number of researchers using a variety of approaches. Gale et al. (1979) described hydraulic testing of boreholes for the purpose of providing effective aperture size (equivalent single fracture aperture) and fracture distribution data. The downhole testing equipment consisted of a double packer system having temperature monitoring capabilities with pressure measurements in, above and below the test zone. Three distinct test interval lengths were used in evaluating the in situ hydraulic properties of the Stripa granite. Initially, boreholes were tested along their entire length using 2 m packer spacings. Then distinct fractures or fracture sets were tested using a packer spacing sufficient to enclose the discontinuity. Finally, test intervals of 6 to 10 m were used in testing what are described as larger fracture/geophysical zones.

The steady state portion of the constant head injection tests was analyzed to yield values of equivalent single fracture aperture (esfa) and equivalent porous medium hydraulic conductivities equal to a bulk hydraulic conductivity for the test interval. Values ranged from approximately

5×10^{-11} to 5×10^{-8} m/s in selected portions of SBH-1 below 200 m in depth for 2 m test intervals (see Appendix A.1). Similar testing methods and intervals yielded hydraulic conductivities of 5×10^{-10} to 1×10^{-7} m/s in the subsurface borehole R4. A hydraulic conductivity tensor was calculated based on a knowledge of fracture orientations and spacings (from core logging and downhole televiewer) and assumed aperture distribution models based on esfa calculations. Scalar and directional hydraulic conductivities and permeabilities are presented in Appendix A.1.

A larger scale assessment of hydraulic conductivity was conducted in the subsurface by measuring the inflow of water to an isolated section of the ventilation shaft excavation. The excavation measured 5 x 5 x 33 m and was situated at the 338 m level of the former mine (Gale et al., 1982). The study objective was to measure the hydraulic properties of a 200,000 m³ rock mass during an 11 month test run to steady state. Pressure measurements (90 points) were conducted in 15 HG- and R-series boreholes radiating out from the test room using interval lengths of 5 m which typically enclosed 15-20 fractures. Inflow of water to the room was measured by collecting water vapour and calculating the net moisture pick-up. The test was conducted at elevated temperatures to assist in water vapour measurement. The test data were analyzed assuming net moisture as radial flow. Hydraulic conductivities calculated using this method were approximately 1×10^{-10} m/s with little change noted at test temperatures ranging from 20 to 45°C. This approach displayed good correspondence to porous media type flow (i.e., straight line observed on a plot of drawdown versus logarithm of time).

Lundstrom and Stille (1978) discussed another large scale hydraulic conductivity test at the 360 m level of the mine

conducted at test places number 1 and 2 (see Section 5.1.1). The test methodology consisted of injecting water into the 16 peripheral boreholes at a number of different pressures and monitoring flowrate at a central hole. A number of different pressure differentials and temperatures were utilized. Test results revealed no radical changes in hydraulic conductivity with different test pressures although only a limited number of tests were conducted. Mean values ranged from 5.1×10^{-10} to 9.6×10^{-10} m/s at 300 kPa to 5.5×10^{-10} to 8.8×10^{-10} m/s at 100 kPa at test places 1 and 2. Heating of injection water from 10°C (background) to 35°C resulted in a decrease in hydraulic conductivity.

Single borehole testing was also conducted at this same site using single and double packer configurations. Water loss tests (constant head injection) were conducted along with television surveys. Lundstrom and Stille (1978) justified a porous media type analysis for the single borehole injection testing based on their observations of an even distribution in water loss throughout all the boreholes tested with only a few tight zones encountered. The tests revealed no significant difference in hydraulic conductivities was observed at injection pressures of 300 and 900 kPa. These tests further revealed that the end effects in a single packer test are significant at the scale of testing conducted and that this leads to a higher hydraulic conductivity for double packer tests over single packers tests (maximum 7 times greater) (Lundstrom and Stille, 1978).

Olkiewicz et al. (1978) discussed water loss tests in two horizontally drilled holes (DBH1 and DBH2) at various test interval lengths (single packer tests) before and after blasting a nearby tunnel. Olkiewicz et al. (1978) also discussed a test in DBHV1 which is a vertical borehole at the

410 m level. Double packers were used to isolate test intervals of 6.68 m in which hydraulic conductivity was assessed by shutting in the interval and monitoring pressure build-up. Hydraulic conductivities were also measured in larger test intervals by monitoring flowrate versus time from that interval to the top of the borehole. These hydraulic conductivities varied from 1×10^{-10} to 2.6×10^{-8} m/s for test intervals between 6.68 m and 460.88 m and depths of 410 to 880 m below ground surface (Olkiewicz et al., 1978).

Laboratory evaluations of Stripa core were discussed primarily by Forster and Gale (1980a) and Thorpe et al. (1980). Forster and Gale (1980a) discussed the test methodology and results of conducting steady-state, constant head injection tests and transient pressure pulse tests of both fractured (parallel to core axis) and unfractured core samples. Hydraulic conductivities, likely indicative of fracture hydraulic conductivities, ranged from 0.20×10^{-4} to 1.41×10^{-4} m/s using injection tests and 1.14×10^{-5} to 1.29×10^{-4} m/s using pulse tests. Both tests were conducted at several confining pressures.

Borehole compliance and temperature effects were also evaluated using a simulated borehole by Forster and Gale (1980a). Results of this testing (Appendix A.1) showed that pulse tests generally yield hydraulic conductivity values on the order of 50-110% lower than hydraulic conductivities determined from injection tests. This difference was attributed to packer compliance effects, which tend to be smaller for the injection tests as the test interval pressure is constant. Forster and Gale (1980a) recommended the use of water filled packers (less compliance), stiff packers (less creep) and extensive lab testing of downhole instrumentation to evaluate performance and quantify such factors as compliance.

Thorpe et al. (1980) document the methodology and results from laboratory testing of an ultra large core of granite from the 360 m level. The core, measuring 1 m in diameter by 2 m in length, had an in situ bearing (parallel to core axis) of S14°W at a dip of 15°. The core was intersected by two main fracture sets with numerous other discontinuities. Of the two main fracture sets, one was oriented parallel to the core axis and was relatively continuous throughout the core while the other was oriented at 25° to 30° to the axis. A large triaxial test machine was used to apply of an axial load to the core ends and a fluid pressure to the core exterior. A simulated borehole was installed in the center of the core to facilitate hydraulic testing. Initially, falling head tests were used to estimate the range of hydraulic conductivities in various intervals along the simulated borehole under no axial stress. Later, steady state constant head injection and withdrawal tests were conducted with a number of axial loads and fluid pressures. Results showed that for the same gradient, flow rates were higher for injection tests than for withdrawal tests. This observation was attributed to opening and closing of fractures at various pressures. The hydraulic conductivity (fracture) of the ultra large core was approximately a factor of two greater than that obtained from previous tests and varied from 2.46×10^{-2} to 1.64×10^{-1} m/s. However, it is uncertain whether this effect can be attributed solely to scale effects. The hydraulic conductivity of the ultra large core may have been enhanced by one or all of the following:

- blasting of the subsurface excavation may have induced fracturing in the vicinity of the ultra large core;
- stress release due to excavation of the tunnel may have induced fracturing;

- core separation during sample preparation;
- differences between the laboratory induced state of stress and that encountered in-situ;
- inadequacies in the parallel plate model for fracture flow for the test conditons.

5.1.3 Porosity

Studies assessing the porosity of the Stripa granite are relatively few in number. The primary ones being those of Gale et al. (1982a,b) and Lundstrom and Stille (1978).

Gale et al. (1982a,b) described a technique to determine effective and total porosity based on a knowledge of the dominant fracture sets, the statistical distribution of fracture trace lengths and spacings, aperture versus stress relationships and fracture roughness. At the Stripa site, the amount of data collected by various researchers permitted application of this method. The results indicate that the rock mass had a mean effective fracture porosity of 10^{-5} and a mean total porosity of 10^{-4} . Detailed results are presented in Appendix B.1.

In Lundstrom and Stille's (1978) studies, a tracer test technique was used at one of the test places described previously. The test involved injection of a fluorescent tracer, called Amidorhodamine G, in each of 16 perimeter boreholes and monitoring its arrival at the central withdrawal well. In this test, an effective porosity of 10^{-4} was determined (see Appendix B.1).

5.1.4 Fracture Properties

Gale et al. (1979; 1982a,b), Olkiewicz et al. (1978), Lundstrom and Stille (1978), Thorpe (1979) and Thorpe et al. (1980) are the main sources of fracture information on the Stripa site. Of these, Gale et al. (1979; 1982) and Thorpe (1979) provide the most detailed analysis of the fracture data. Gale et al. (1979) document the collection of basic data on fracture orientations, spacings and continuity gathered by mapping the fractures of surface outcrops and in the walls and floors of the subsurface excavations. Careful core drilling, reconstruction and orientation were conducted in order to determine the variation in fracture geometry which, when combined with fracture data from outcrops and excavations, aided in characterizing the three-dimensional fracture system. Television logs were used to verify orientations of fractures from cores and equivalent single fracture apertures (from injection tests) were used as a check on measured apertures and their location.

Gale et al. (1982a,b) analyzed a large array of fracture data including trace lengths and fracture distributions in the ventilation drift and HG and R series boreholes. They found that trace length data was best fit with a negative exponential distribution and that fracture spacing data was best fit with a lognormal distribution. Their analysis also revealed the presence of four dominant fracture sets shown in a lower hemisphere plot in Appendix C.1. One set strikes northwest and has a near horizontal dip. Two of the remaining three sets are steeply dipping and have strikes to the west-northwest and north. The one remaining joint set dips at 70° to 80° and strikes to the north-northeast. Analysis of fracture trace lengths suggests that the trace lengths are significantly different in each of these fracture sets. Spacing of fractures along a borehole which fall within the same set are also documented (see Appendix C.1).

Thorpe (1979) presents the methodology and results of a detailed study of geologic discontinuities associated with the time-scale heater test excavation. This study involves extensive fracture mapping of core and the floor of the experimental tunnel (Appendix C.1). Thorpe (1979) identified four north striking shear fractures which dipped steeply. These were attributed to oblique thrust faulting producing displacements up to 2 m. In addition, four distinct fracture sets were observed to exist locally, one of which coincided with the shear fractures. One of the fracture sets is near horizontal with the remaining steeply inclined. Fracture length and spacing distributions were found to be lognormal. Two of the fracture sets were found to be perpendicular to the principle stress direction and one of the sets was found to be perpendicular to the minor principle stress direction. This latter fracture set post dates other fractures and is attributed to isostatic rebound.

In other studies, Olkiewicz et al. (1978) present the results of in-depth studies of geology at various levels in the Stripa mine including fracture mapping of cores and tunnel. Rose diagrams for mapping conducted on surface outcrops show a primary joint set striking to the northeast. A second set, striking N10°E, is observed less frequently and a third and fourth set striking N80°W and N85°E are observed even less frequently. Lundstrom and Stille (1978) document fracture mapping at hydrologic test sites at the 360 m level. Thorpe et al. (1980) presented results of studying a large core sample.

The fracture data available for the Stripa site is very extensive and has only been briefly summarized here. Detailed diagrams summarizing these studies are presented in Appendix C.1.

5.2 Swedish Sites

5.2.1 Site Description

The Swedish program for the disposal of spent nuclear fuel involves placing the waste at depth (approximately 500 meters) in crystalline rock formations. Potential repository sites are evaluated in accordance with a standard program which is regularly revised and updated as a result of experience gained in ongoing studies. According to Carlsson et al. (1984), six sites have been evaluated so far. These sites, shown in Figure 5.5 represent different geological and topographical conditions. Of these sites the investigations of the four sites after 1979 (i.e., Fjallveden, Gidea, Kamlunge, Svartboberget) have been in accordance with this standard program. Site descriptions for these four sites are provided in Olsson and Ahlbom (1984) as follows:

"Site Fjallveden, 80 km southwest of Stockholm, which is characterized by flat topography with minor fracture valleys in a north-westerly direction. The bedrock consists of veined gneiss with steeply dipping strata of granite gneiss." (Ahlbom et al., 1983a.)

"Site Gidea, 30 km northeast of Ornskoldsvik, is situated within a plateau with an area of 100 km². Within the site the topography is flat. The bedrock consists of veined gneiss with strata of granite gneiss with a small dip." (Ahlbom et al., 1983b.)

"Site Kamlunge, 65 km northeast of Lulea, is situated on a plateau with an area of 16 km², which is about 100 m above the surrounding valleys. The bedrock consists of gneisses and red granite. Within the site a horizontal



Figure 5.5 Sites investigated in Sweden (after Olsson and Ahlbom, 1984)

fracture zone has been found at a depth of 500 m."
(Ahlbom et al., 1983c.)

"Site Svartboberget, 12 km west of Edsbyn, is situated on a 2.5 km wide and 5 km long ridge. The surrounding valleys, which have a northwesterly direction, are at a level 75-85 m below the top of the ridge. The bedrock consists of a strongly metamorphosed gneiss, migmatite. Characteristic for this site is the presence of minor fracture zones with a mutual separation of 30-80 m."
(Ahlbom et al., 1983d.)

As part of the safety assessment for potential repository sites, data describing the subsurface hydrology (and more specifically, the fracture properties) are essential. Studies at these sites consist of surface and subsurface examinations aimed at identifying the geometry and properties of fracture zones and include fracture mapping, core logging, borehole geophysical measurements and hydraulic testing. This approach is discussed in detail in Olsson and Ahlbom (1984) and normally consists of drilling approximately 10 boreholes, 600 to 1000 m in length once a potential site is identified from preliminary studies (Olsson and Ahlbom, 1984). Table 5.1 after Carlsson et al. (1984) documents the number of boreholes and geology at each of four of the sites under investigation.

Earlier studies (Larsson et al., 1977) consisted of assessing potential repository areas based on geology and tectonics of the Precambrian rock in that area. Larsson et al. (1977) evaluated five geological units in southeastern Sweden, particularly those western parts of the region, including:

- coastal gneisses;
- older granitoids;

Table 5.1 Data on Geology, Boreholes and Number of Measurements on Hydraulic Conductivity at Four Swedish Sites (after Carlsson et al. (1984))

Site	Bedrock	Number of Boreholes	
		> 150 m	< 150 m
Fjällveden	Veined gneiss	15	49
Gidea	Veined gneiss	13	24
Kamlunge	Gneiss, granite	16	21
Svartboberget	Migmatite	7	16

- younger granitoids;
- youngest granitoids;
- dolerites.

The scope of studies at these sites consisted primarily of preparing tectonic-morphological maps which lead to the observation that the coastal gneisses had a different fracture pattern than other areas. Earlier studies of the Precambrian rock involved the evaluation of groundwater inflow to underground storage caverns (Larsson et al., 1977; Lindblom, 1979), assessment of fracture zones using surface and subsurface geophysical techniques (Magnusson and Duran, 1978), downhole hydraulic testing using water loss tests (Hult et al., 1978) and estimation of hydraulic conductivities based on specific drawdown data from domestic water wells (Carlsson and Carlstedt, 1976). Tracer tests were conducted in fractured crystalline rocks at the Studsvik Research Area located approximately 90 kilometers south of Stockholm (Landstrom et al., 1978). At this site, eight boreholes (B1-B8) of 115 mm diameter were installed to facilitate hydraulic testing. More recently, Carlsson et al. (1984) and Olsson and Ahlbom (1984) discussed the hydraulic and geophysical techniques in use in the Swedish repository siting program. Carlsson et al. (1984) presented the results of hydraulic testing of various hydraulic units at four potential repository sites in Sweden (Fjallveden, Gidea, Kamlunge and Svartboberget). The hydraulic units examined included regional fracture zones, local fracture zones, and the rock mass itself. Olsson and Ahlbom (1984) discussed the Swedish experience in the use of geophysical techniques and, in particular, the use of borehole cross-hole techniques for mapping fracture zones.

5.2.2 Permeability

Studies of hydraulic conductivity as part of the Swedish repository siting program are discussed by Hult et al. (1978),

Carlsson and Carlstedt (1977) and Lindblom (1979). Carlsson and Carlstedt (1977) attempted to utilize flow rates and drawdowns from tests conducted by water well drillers in order to estimate the transmissibility and hydraulic conductivity of fractured crystalline rock. Statistical analysis of pump test data was conducted and well losses were accounted for. Results suggested that gneisses were somewhat more permeable than granites but that this was a function of the degree of tectonic activity. Mean hydraulic conductivities and hydraulic conductivities in the 40-60% interval of the normal distribution are presented in Appendix A.2).

Hult et al. (1978) summarized hydraulic testing at several different areas of Sweden; namely, Krakemala, Avro, Finnsjon, Forsmark and Karlshamn (see Appendix A.2). Water loss tests (constant head injection tests) were conducted using double packers with test interval lengths of 2 to 3 m in near vertical boreholes. Several injection pressures were utilized (0.2, 0.4 and 0.6 MPa) with possible packer by-pass identified at higher injection pressures. Results are summarized as graphs of hydraulic conductivity versus depth for each borehole and typically varied from the detection limit of approximately 3×10^{-9} m/s to a maximum of 10^{-4} m/s (see Appendix A.2).

Lindblom (1979) discussed a method for assessing large scale permeability/hydraulic conductivity by measuring the inflow of groundwater to a large underground storage cavern. The experiment, conducted at the 120 m level, consisted of injecting water into boreholes above the caverns at controlled pressures and flowrates and monitoring inflow to the cavern. Hydraulic conductivities were also evaluated using packer tests (constant head injection tests) in the boreholes above the

caverns (see hydraulic conductivity versus depth plots in Appendix A.2). Comparable hydraulic conductivities were obtained from each test method suggesting no scale effects for the volume of rock sampled by these techniques. Larson et al. (1977) also measured inflow to caverns as a method of characterizing the rock mass.

Carlsson and Olsson (1977b), in a study unrelated to repository siting studies, summarize hydraulic conductivity values for Forsmark, Juktan, Ringhals, Ylen, Stensjon and Glan in the form of hydraulic conductivity versus depth plots. Many values were observed in the 10^{-7} to 10^{-5} m/s range but values as low as 5×10^{-11} m/s were also measured. These values, derived from analysis of water loss tests, are further analyzed to evaluate their dependence on depth.

More recently, Carlsson et al. (1984) described hydraulic test programs at four potential repository sites (i.e., Fjallveden, Gidea, Kamlarge, Svartboberget). Constant head injection tests were conducted followed by pressure recovery monitoring until formation pressures were achieved. Testing was conducted in different hydraulic units including regional fracture zones, local fracture zones and the rock mass. Test data was analyzed using the continuum approach and is presented in Appendix A.2 as hydraulic conductivity versus depth diagrams. Measured values varied widely from site to site and with depth. Results of this program concluded that the use of steady state and transient testing reduces equipment compliance effects and provides more reliable hydraulic conductivity estimates in tight zones.

5.2.3 Porosity

Although considerable work has been done in characterizing crystalline rocks in the Swedish program for repository siting,

little effort appears to have been directed at obtaining measurements of porosity. Most of the work that has been done is reported in Skagius and Neretniks (1983). They obtained porosity measurements on cores using both a mercury infusion technique and a leaching technique. Typical values range from 0.06 to 0.33 % while detailed results of their investigations are reported in Appendix B.2.

5.2.4 Fracture Properties

Studies of fracture characteristics for the Swedish program are described by Larsson et al. (1977), Landstrom et al. (1978) and Hult et al. (1978) (see Appendix C.2). Larson et al. (1977) prepared a tectonic-morphologic map for southeast Sweden in which two post crystalline compression stages were identified striking N5°E and N20-25°E. Of the five geologic units studied, the coastal gneisses were found to have a different fracture pattern from the remaining areas examined; the main difference being that distinct vertical tension joints parallel to the compression axis were missing (see lower hemisphere plots, rose diagrams in Appendix C.2). This observation, in conjunction with hydraulic testing (i.e., cavern inflow studies) lead to the conclusion that the coastal gneisses were most suited for "underground storage work" due to the resistance of the formation to lateral stress in the earths crust.

The work of Landstrom et al. (1978) is limited to fracture mapping at surface in the vicinity of the Studsvick Research Station (see Appendix C.2).

Hult et al. (1978) provide the most extensive coverage of fracture data for the Swedish research sites. The lower hemisphere plots, TV scan and single point resistance measurements are provided for Krakemala and Karlshamm and complete geophysical surveys are presented for Krakemala, Avro, Finnsjon, Forsmark and Karlshamm (Appendix C.2).

Olsson and Ahlbom (1984) provide plots of fracture frequency versus depth for borehole KM 12 at Kamlunge and borehole FJ5 at Fjallveden.

5.3 Finnish Sites

5.3.1 Site Description

In Finland, nuclear power is generated by two organizations: Imatran Voima Oy (IVO, Imatra Power Company) and Tedlisuuden Voima Oy (TVO, Industrial Power Company Ltd.). In 1978, these organizations formed a joint Nuclear Waste Commission of Finnish Power Companies (YJT) in order to plan and coordinate research and development in the field of radioactive waste management. These two companies are the main research groups involved in the hydrological aspects of nuclear waste disposal in Finland. Research sites have been established at IVO's generating plant at Olkiluoto (Figure 5.6) and at TVO's generating plant at Loviisa (Figure 5.7) on the island of Hasholmer. An additional hydrological research area has been established by YJT at Katossuo in Lavia (Figure 5.8) primarily to aid in equipment and test methodology development for candidate area evaluations. Other organizations involved include the Geological Survey of Finland, Technical Research Center of Finland, the Department of Radiochemistry at the University of Helsinki, private sector consultants and the Swedish Geological Survey.



Figure 5.6 Investigation Area at Okiluoto Finland (after Laine and Tikkanen, 1982)

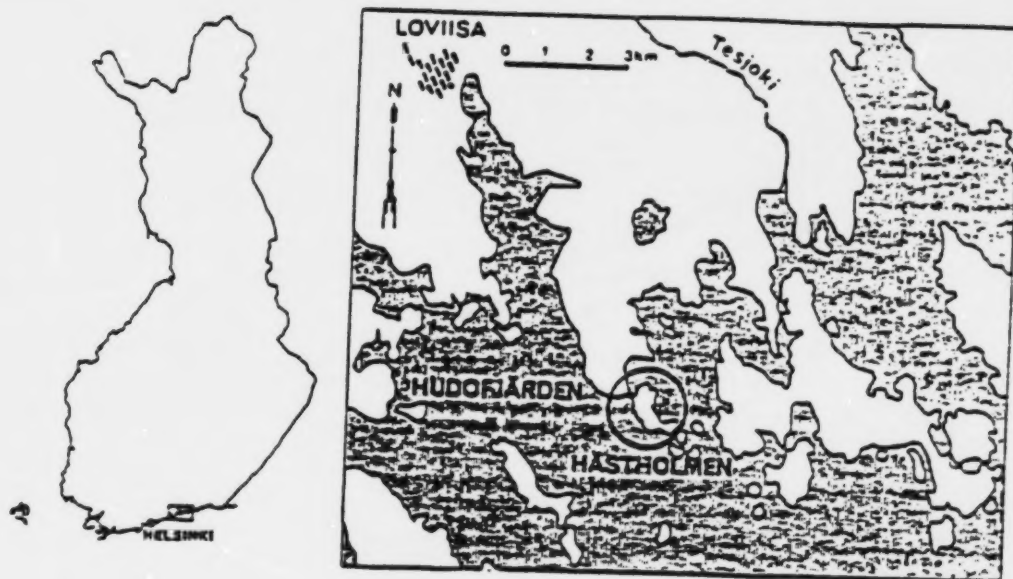


Figure 5.7 Location of the Loviisa Power Plant Site in Finland (Gardemeister and Rouhiainen, 1984)

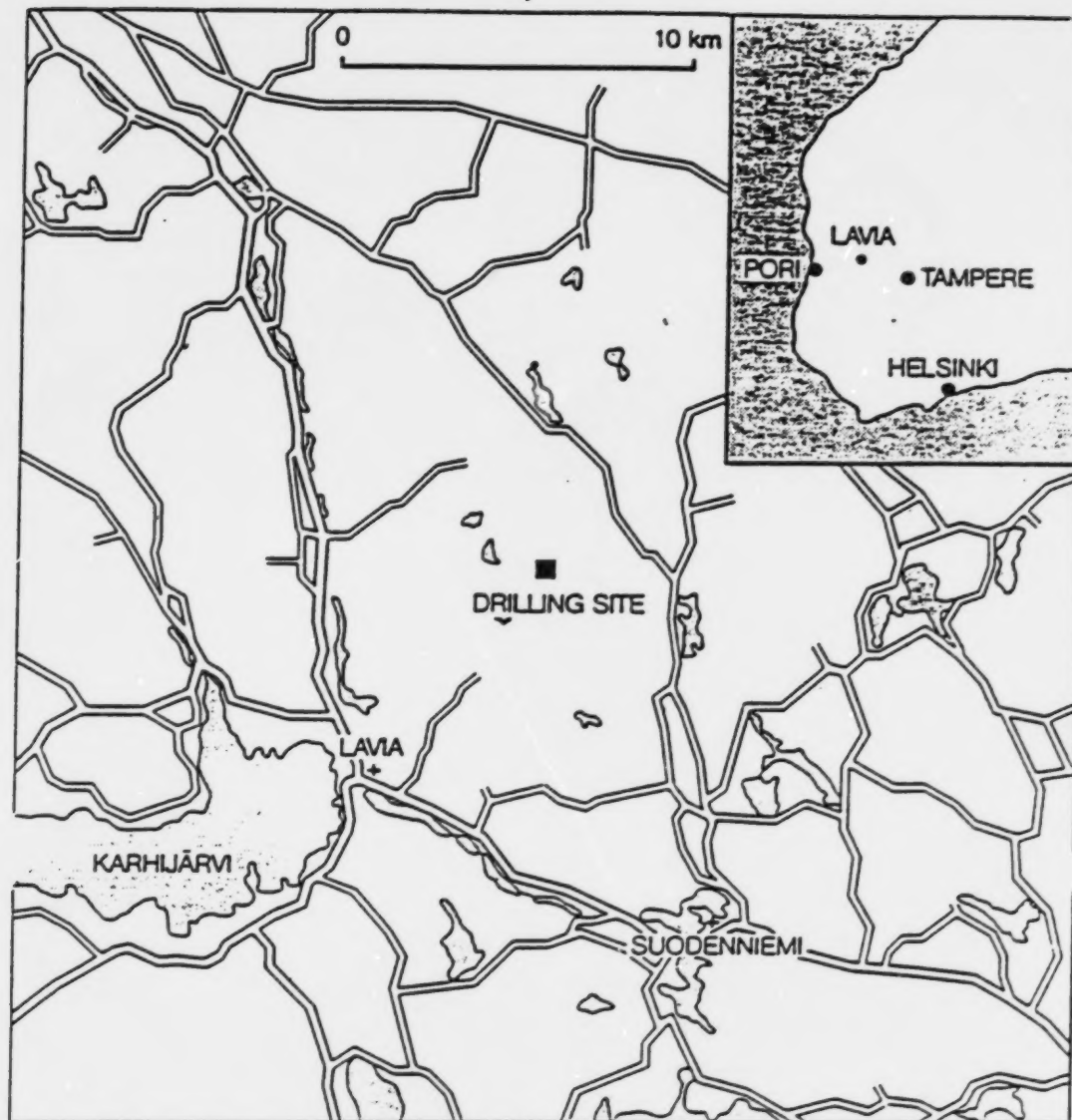


Figure 5.8 Location of the Lavia Drill Site in Southern Finland (after Almen and Persson, 1984)

The Finnish concept for the disposal of high level nuclear waste involves placement of packed and/or solidified wastes into repositories constructed 50 to 100 m deep in crystalline rock. The Precambrian Finnish bedrock forms part of the Baltic Shield (Figure 5.9) and has been described as offering a desirable environment for waste disposal due to its high strength and stability, resistance to weathering and slow groundwater flow rate and recharge (Aikas, 1983). Vuorela and Hakkarainen (1982) reported that the most favourable repository sites are in Central Finland as well as in the northern and eastern parts of the country; however, they also reported that none of the bedrock in the entire country could be classified as completely unsuitable for further site investigations.

A brief summary of each site and its characteristics is provided below:

Loviisa

The Loviisa site is situated on the island of Hasholmen in the Gulf of Finland (Figure 5.6) off the southern coast of the country. The site is approximately 80 km from Helsinki in an area which is quite flat with local relief usually less than 20 m. The bedrock at the site is part of the western portion of the large Precambrian Wyborg rapakiva granite massif or pluton (Gardemeister and Rauhiainen, 1984). A thin overburden of till moraine overlies the granitic bedrock to a depth of several meters. Investigations conducted for the site include geological mapping, core drilling to 200 m, geophysical surface measurements, permeability tests and groundwater sampling as well as a number of lab tests (Gardemeister and Rauhiainen, 1984). Eight boreholes, up to 200 m in depth and 70 to 150 m apart, were drilled between 1980 and 1982 (see Figure 5.10,



- PALEOZOIC AND YOUNGER SEDIMENTARY ROCKS
- ▣ PALEOZOIC IGNEOUS ROCKS
- ▤ CALEDONIDES
- ▥ JOTNIAN FORMATIONS
- ▦ GENTLY FOLDED DALSLANDIAN FORMATIONS
- ▧ DALSLANDIAN GRANITES
- ▨ DIABASES
- ▩ GOTHIAN GRANITES AND RAPAKIVI GRANITES
- VOLCANIC ROCKS
- SVECOKARELIDIC SCHISTS AND GNEISSES
- ▬ SVECOKARELIDIC PLUTONIC ROCKS
- ▮ PRESVECOKARELIDIC BASEMENT COMPLEX
- ▯ BASEMENT COMPLEX OF UNKNOWN AGE

Figure 5.9

The Baltic Shield and Formations Bordering It (after Aikas, 1983)

Table 5.2). The boreholes are 66 mm in diameter and are both vertical and horizontal.

Olkiluoto

The Olkiluoto site, operated by IVO, is situated on the Ulkopaa Peninsula adjacent to the Gulf of Bothnia (Figure 5.6) as reported by Laine and Tikkanen (1982). IVO, in conjunction with the Geological Survey of Finland, carried out mapping, sounding and drilling investigations primarily in the area owned by IVO (see Figure 5.11 for borehole locations).

The geology of the Ulkopaa Peninsula consists primarily of medium to coarse grained tonalite or granodiorite overlain by a sandy till with some boulders and rock near the land surface (Laine and Tikkanen (1982)). The strike of schistosity at the site is almost east-west (75-100°) with a dip of 60-65° to the south.

A number of boreholes have been drilled at the site commencing with two boreholes in 1980 (YD1 and YD2) (Figure 5.11). These are summarized as follows (Laine and Tikkanen, 1982):

YD1, YD2

- YD1 is vertical, YD2 inclined (unspecified angle)
- approximately 200 m deep, 66 mm diameter
- geology summarized in Laine and Tikkanen (1982)
- installed by coring in 1980

YD4-YD7

- 90 to 132 m in length
- installed by coring in 1981

Table 5.2 Geological Studies Performed at the Loviisa Site (Hastholmen Island) during 1980-1983 (after Gardemeister and Rouhiainen (1984))

Study	Quantity
Geological mapping	
Rock drilling	
Diamond core drilling	8 boreholes (Y1, Y2, Y4, Y5, Y7, Y8, Y10, Y11), totally 1576.87 m
Percussion drilling	1 borehole (Y3), 72.50 m
Soil drilling	
Light static-dynamic sounding	61 pcs
Diamond core drilling	1 borehole (Y9), 22.85 m
Geophysical surface measurements	
Echo sounding	11 lines, totally 3.9 km
Seismic refraction sounding	18 lines, totally 10.65 km
Earth resistivity sounding	9 sounding points
Geophysical borehole measurements	
Electrical resistivity measurement	at intervals of 0.5 m (Y1...Y8)
Focused resistivity measurement	at intervals of 0.2 m (Y1...Y8)
Groundwater resistivity measurement	at intervals of 0.5 m (Y1...Y8)
Groundwater temperature measurement	at intervals of 0.5 m (Y1...Y8)
Caliper	continuous (Y1, Y4, Y5, Y8, Y11)
Multichannel sonic	continuous (Y1, Y4, Y5, Y8, Y11)
Neutron-neutron	continuous (Y1, Y4, Y5, Y8, Y11)
Gamma-gamma	continuous (Y1, Y4, Y5, Y8, Y11)
Gamma	continuous (Y1, Y4, Y5, Y8, Y11)
Dipmeter	continuous (Y1, Y4, Y5, Y8, Y11)
Rock stress measurement	1 borehole (Y6), 26.85 m
Electric Cross hole (Nise-a-la-Masse)	Sections Y1-Y4, Y1-Y8, Y2-Y7, Y2-Y10, Y2-Y11, Y4-Y5, Y4-Y11, Y5-Y7, Y5-Y8
Seismic cross hole	Sections Y1-Y4, Y4-Y5, Y4-Y11, Y5-Y8
Permeability tests	215 pcs (Y1, Y2, Y4, Y5, Y7, Y8, Y10, Y11)
Groundwater sampling	133 sampling depths (Y1...Y5, Y7, Y8, Y11)
Laboratory studies:	
Core samples	
Thin section study	63 pcs (Y1, Y2, Y4, Y5, Y7, Y8, Y10, Y11)
Fracture infilling analyses	71 pcs (Y1, Y2, Y4, Y5, Y7, Y8, Y10, Y11)
Rock mechanical tests	39 depths (Y1, Y2, Y4, Y5, Y7, Y8)
Groundwater samples	
Chemical analyses	137 pcs (Y1...Y5, Y7, Y8, Y11)
Dating tests	
C-14 determination	18 pcs (Y1, Y2, Y5, Y11)
C-13 determination	9 pcs (Y1, Y2, Y5, Y11)
Tritium determination	71 pcs (Y1, Y2, Y3, Y5, Y11)
Microfossil studies	17 pcs (Y1, Y2, Y5, Y11)
Sorption tests	13 samples

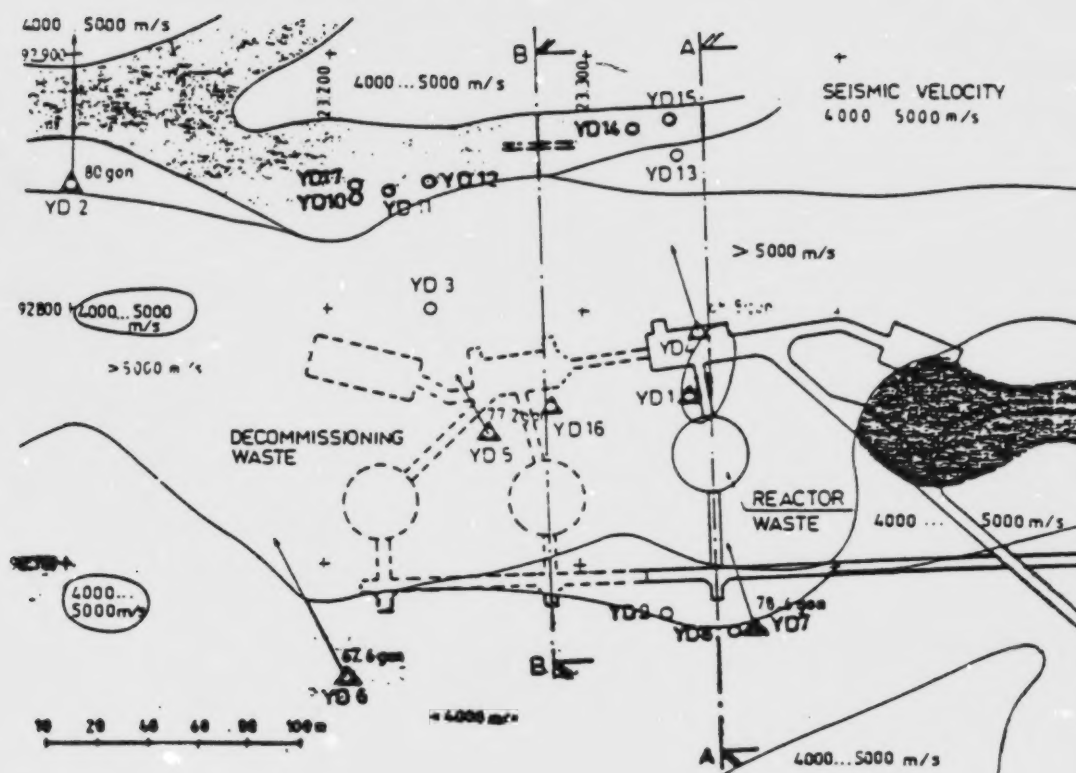


Figure 5.11 Borehole locations at the Olkiluoto Site (after Laine and Tikkanen, 1982)

- geology summarized in Laine and Tikkanen (1982)

YD3

- percussion drilled in 1980
- 73 m deep

YD9, YD11-YD14

- percussion drilled in 1981
- YD9, YD11, YD12 to 30 m deep
- YD13, YD14 to 60 m deep
- 64 mm diameter
- rock flour samples collected

YD8, YD10, YD15, YD17

- percussion drilled
- 155 mm diameter
- YD8, YD10 = 30 m in length
- YD15 = 60 m in length
- YD17 = 50 m in length
- installed as test wells for test pumping

Lavia (Katossuo)

The Lavia (Katossuo) site is located in southwest Finland northwest of Helsinki as shown in Figure 5.8. This site was selected in 1984 primarily for the purpose of developing equipment and test methodologies for use in future candidate site evaluations. A single borehole, 1001 m deep and 56 mm diameter, has been drilled at an inclination of 80° (Almen and Persson, 1984). The main rock types are porphyritic granite and quartz diorite.

5.3.2 Permeability

Hydraulic testing for each of the Finnish Sites is discussed separately, as follows:

Loviisa

Gardemeister and Rouhiainen (1984) briefly discussed the hydrology program at Loviisa. Single and double packer tests were conducted at 3.2 meter test interval lengths at pressures of either 200, 400 or 600 kPa. Only the hydraulic conductivities for borehole Y1 are presented as hydraulic conductivity versus depth (see Appendix A.3). Values varied from 10^{-9} to almost 10^{-5} m/s in this borehole.

Olkiluoto

Laine and Tikkanen (1982) provided a thorough discussion of the hydrologic testing program at the Olkiluoto site. Constant pressure injection tests and pump tests were conducted in numerous boreholes at this site. Constant pressure injection tests were conducted using double packers (3.2 m intervals) in boreholes YD1 through YD5 at pressures of 100, 200, 400, 200 and 100 kPa for durations of 10 minutes at each pressure. Tests were conducted at a test interval length of 10 m in fractured zones. The range of measureable flow rates were a minimum of 0.002 L/min (5×10^{-10} m/s) to a maximum of 50 L/min. Single packer tests were also conducted at approximately 20 m intervals. Laine and Tikkanen (1982) observed that hydraulic conductivities could not be assessed over a large portion of the borehole due to flow rates below the detection limit. Hydraulic conductivities for the tonalite were generally less than 2.0×10^{-6} m/s and slightly higher for the gneiss. Testing results are presented as graphs of

hydraulic conductivity versus depth (superimposed on a geologic section) in Appendix A.3.

Pump tests were conducted in boreholes YD15, YD8, YD10 and YD16 and apparently included the use of tracers; however, translation of documents from Finnish has made this point somewhat uncertain (see GSF, 1982 for greater details). Values for hydraulic conductivity and effective porosity were calculated from these test results. Hydraulic conductivities ranged from 1×10^{-7} to 4×10^{-4} m/s.

Lavia (Katossuo)

Almen and Persson (1984) provide an extensive documentation of the hydraulic test program for the Lavia borehole including test analysis methodologies. At Lavia, transient injection tests were followed by pressure fall-off (pressure decay) in the 1001 m long borehole using a double packer with a 30 m long test interval. The different phases of the test consisted of a 30 min packer sealing, a 2 hr water injection and a 2 hr pressure fall-off (decay). In most cases, the transient portion of the injection test is analyzed except in higher hydraulic conductivity zones. The pressure fall-off (decay) is only analyzed in the lower hydraulic conductivity zones where sufficient data can be obtained (Reported values are presented in tables and figures in Appendix A.3 and range from 9.7×10^{-12} to 5.7×10^{-7} m/s).

A skin factor and effective borehole radius were also calculated. Trends indicated by the data show that there is no apparent correlation of hydraulic conductivity with depth.

5.3.3 Porosity

Effective porosity measurements were conducted on the tonalite/granodiorite/gneiss at the Olkiluoto site using tracer

tests. Also, matrix porosities were calculated on cores of the granite from the Lovissa site using lab methods. Test methodologies for both sources are not well documented. Porosity values are presented in Appendix B.3 and range from 0.002% to 0.08%.

5.3.4 Fracture Properties

Loviisa

Gardemeister and Rouhiainen (1984) present the results of mapping exact location, orientation and apertures of fractures (approximately 500 fractures mapped) including documentation of fracture infilling materials. Two steeply dipping fracture sets were observed at the Loviisa site; one strikes northwest to southeast and a second perpendicular to the first. A third set was observed with a north-south strike and a shallow dip towards the east. Fracture spacing was observed to vary considerably in different directions on the outcrops mapped. Spacings were greater than 1 m but did occur at values as high as several meters (Gardemeister and Rouhiainen, 1984). Fracture spacings in cores were reported as widely to medium spaced with values as low as 0.3 meters in zones of high fracturing.

Fracture zones were observed to vary from one to several meters in thickness and were generally encountered at depths greater than 50 m below sea level. These fractured zones generally dip gently to the east with little infilling. The continuity of these fracture zones is somewhat uncertain (limited data on fracture properties presented in Appendix C.3).

Olkiluoto

Laine and Tiokkanen (1982) report the primary fracture set strikes as 160° to 170° and 250° to 270° and, to a lesser extent, 10° to 30°. These joints are mainly individual with neither dense jointing nor fractured structures observed in outcrops. Fracture frequencies versus depth are presented on geologic cross-sections in Appendix C.3.

Lavia (Katossuo)

Fracture data was not encountered for this site.

5.4 Nevada Test Site

5.4.1 Site Description

The Nevada Test Site (NTS) (Figure 5.12) was the location for the first of a series of underground nuclear explosions conducted in 1957 by the United States Atomic Energy Commission as an alternative to earlier surface and aerial detonations and their associated radioactive fall out. One possible side effect of these underground detonations was the potential for contamination of the groundwater system by radionuclides. The United States Geological Survey (USGS) was requested to study the occurrence and movement of groundwater beneath the NTS with the primary objective to evaluate the potential for aquifer contamination in the vicinity of the detonations.

More recently, plutonic environments became a source of interest as potential sites for nuclear waste repositories. At the NTS, a number of shafts and drifts had previously been excavated into the Climax Stock to facilitate testing of nuclear weapons. This ease of access to a large granitic body

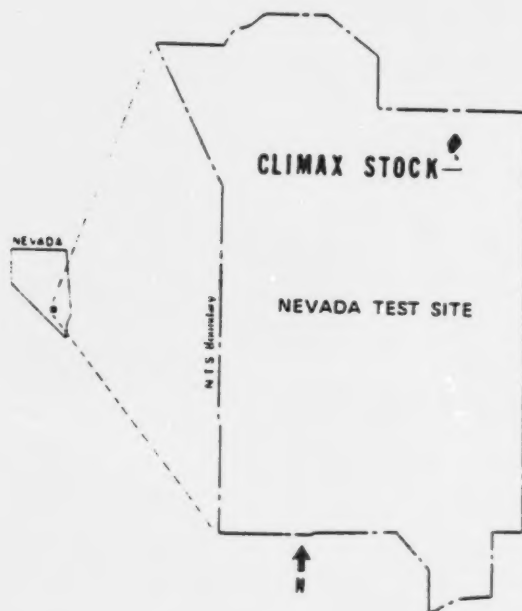


Figure 5.12 Location of the Nevada Test Site (Wilder and Yow, 1984)

in the depth range of interest resulted in the selection of the Climax Stock as a research site for evaluating potential repositories.

The geology of the area consists of a thick sequence (originally more than 11,280 m) (Wilder and Yow, 1984) of sedimentary deposits overlying Precambrian basement rocks. Complex folding and faulting of the sedimentary rocks of Paleozoic age has occurred after which they were overlain by Tertiary volcanic tuffs and lavas and latter alluvium in the valleys. During the Mesozoic time, three granitic plutons (Climax, Twinridge, Gold Meadows) intruded through the Precambrian and lower Paleozoic sedimentary formations (see Wilder and Yow, 1984 for a more complete discussion of the area geology and geomorphology).

The Climax granite was described by Murray (1980) as follows:

"The Climax Stock is a granitic rock mass that has intruded through Paleozoic sedimentary rocks and Tertiary volcanics at the northern end of NTS, where it crops out over an area of 4 km² (see Figure 5.13).

This pluton is conical in shape with an area of approximately 100 km² at a depth of several kilometers (Wilder and Yow, 1984). The Climax consists of a quartz monzonite and a granodiorite unit with a dipping contact. Two shafts, the "Tiny Pot" and the "Pile Driver", were excavated for nuclear tests. The Pile Driver shaft has extensive horizontal tunnels related to several subsurface detonations. At both the 250 m and 420 m level, drifts were excavated in relation to these detonations. It is at the 420 m level where most hydrologic studies have been conducted. Existing drifts at the 420 m level were extended in size primarily to facilitate heater experiments referred to as the Spent Fuel Test - Climax

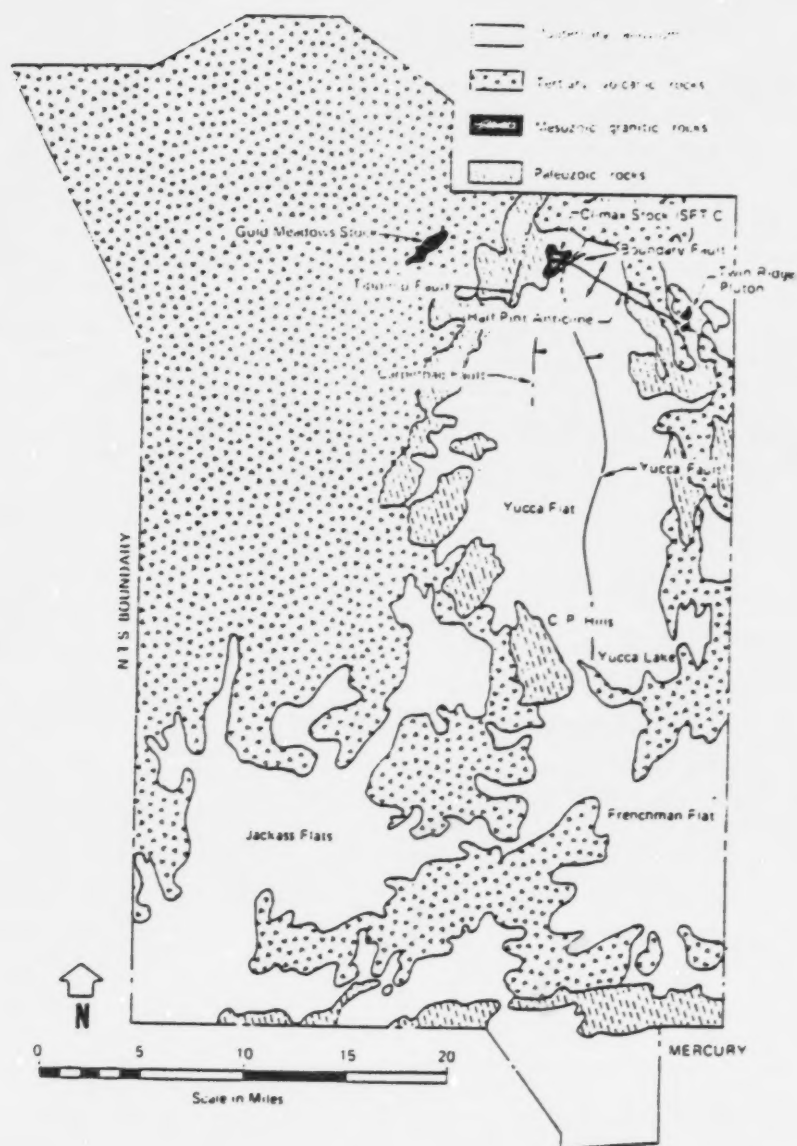


Figure 5.13

Nevada Test Site Geology (after Wilder and Yow, 1984)

(SFT-C). The drifts for these tests were selected based on subsurface geology, available facilities, subsurface topography and the desirability to cross major joints at right angles.

Isherwood et al. (1980) described a program plan for assessing hydrogeological and geochemical processes at the NTS. Proposed hydraulic testing included "conventional water packer tests" to be conducted in situ and radionuclide tracer tests to assess partitioning of radionuclides in granitic media. Transport properties (e.g., partitioning coefficients) of the granitic media were also to be assessed in the lab on crushed and intact cores.

Studies of a hydrologic nature include extensive mapping of fractures of both core and subsurface excavations such as that of Wilder and Yow (1984) who mapped in excess of 2500 fractures. Boreholes installed at the site are documented by Ballou (1979), Murray (1980), McMullen and Pasternak (1970), Isherwood et al. (1981) and Wilder and Yow (1984). McMullen and Pasternak (1970) provided little documentation on three boreholes designated A, B and C in which hydraulic tests were conducted following the Pile Driver event. Ballou (1979) as referenced in Murray (1980) discussed testing of 5 boreholes installed as part of the heater tests. These boreholes, for which no designations were given, are 48 to 76 mm in diameter and 9 to 12 m in depth. Murray (1980) also referred to Walker (1962) who discussed 11 test holes drilled by the USGS in the late 1960's. These boreholes are 215 to 610 m in depth. Isolated lost circulation zones were reportedly encountered during drilling although 100% drill water recovery occurred over most of the borehole. Isherwood et al. (1981) described hydraulic interference testing in three pairs of horizontal boreholes (near the SFT-C drift). These wells are designated as TT-1 through TT-6. Ten individual fractures were selected

for testing; two of which showed good hydraulic connection between boreholes and were identified for future tracer testing.

Wilder and Yow (1984) discussed the drilling of boreholes UG-1 to UG-4 from drifts at the 420 m level in order to confirm the structural geology described by Maldonado (1977) (Figure 5.14). Further coring was reportedly conducted in order to install additional instrumentation and is described in Wilder et al. (1982). Wilder and Yow (1984) presented the results of fracture mapping primarily for the Tail Extension drift and heater drifts associated with SFT-C experiments. Mapping results and techniques are presented in Wilder and Yow (1981).

5.4.2 Permeability

From references reviewed regarding studies at the NTS, it is apparent that much of the effort has been devoted to fracture mapping and fracture characteristics. Measurement of hydraulic conductivities, is, for the most part, relatively limited.

The earliest assessment of the hydraulic properties of the Climax granite was that of McMullen and Pasternak (1970). These researchers initially utilized a five foot (1.5 m) distance between straddle packers to measure intrinsic permeabilities in boreholes A, B and C. Following lodging of this packer in borehole B, a second set of straddle packers (of unspecified spacing) was constructed. Data were obtained for both flow and pressure decay periods using air as the injection fluid. Permeability values varied from 5.4×10^{-11} to 1.1×10^{-9} cm². It is uncertain whether steady-state conditions were reached during the injection test and whether

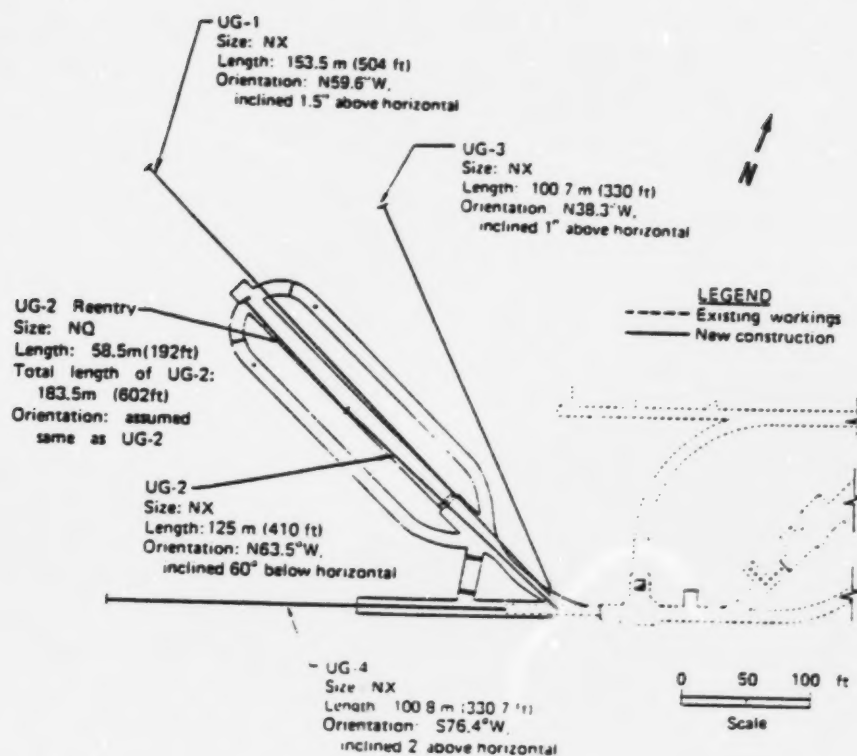


Figure 5.14 Exploratory Subsurface Boreholes at the Nevada Test Site (after Wilder and Yow, 1984)

transient or steady state data were analyzed to yield the permeabilities reported (see tables, Appendix A.4).

A later testing program is discussed briefly in Ballou (1979) as referenced by Murray (1980). This program involved the use of air in transient pressure pulse tests conducted in five boreholes of 9 to 12 m in depth (located near the heater experiment drift). Testing included six repressurizations over an 83 day testing duration. Intrinsic permeabilities obtained were less than 10^{-9} darcies (10^{-21} m²) and were considered to be representative of the rock matrix.

Isherwood et al. (1981) conducted cross-hole interference tests (presumably constant head, constant flow injection tests) by injecting water into a selected fracture in one borehole and monitoring the response in different boreholes. Fluid was injected at boreholes TT-2 and TT-6 and monitored at TT-1 and TT-5 respectively. Due to the fact that the test site is located in the unsaturated zone, the fractures were saturated prior to testing through the addition of water. Straddle packers were used (interval unknown but thought to be sufficient to just isolate selected individual fractures) and tests were conducted at pressures of 323 and 462 kPa. Test data analysis was based on radial flow between two parallel plates and reported as intrinsic permeabilities (33 to 75 μm^2) and calculated apertures. Good interconnection between the borehole pairs (as evidenced in the high monitoring well flowrate) lead to the conclusion that the site is appropriate for radioactive tracer tests between wells (see Appendix A.4).

5.4.3 Porosity

Measured values for porosity of the Climax granite at the NTS were very few in number in the literature reviewed. Measured values for fine and medium grained quartz and granodiorite were presented in Maldonado (1977) as measured by Izett (1960). Average values from between 8 and 16 samples were presented along with ranges in values (0.003% to 0.05%). No documentation is presented on the method of porosity measurement used (See Appendix B.5.)

5.4.4 Fracture Properties

Thorpe and Springer (1981), Thorpe (1984) and Wilder and Yow (1984) present data related to fracture characteristics in the Climax Stock at the NTS. Thorpe and Springer (1981) map and characterize major geologic discontinuities at the 420 meter level in the Climax granite adjacent to Lawrence Livermore Laboratories spent fuel test (SFT-C). Their efforts were concerned only with fractures which may convey appreciable amounts of water. Small fractures with little interconnection or those which may have been opened due to mining of the excavation (i.e., blasting) were omitted from the study. The total number of fractures and faults mapped in the main access and tail drifts was approximately 90. During mapping, three predominant fractures sets were identified: NW strike with vertical dip, NE strike with vertical dip and NW strike with subhorizontal dip. Frequency of major fractures was higher in the main drift and fractures tended to be braided, stepped or en echelon while those of the tail drifts were more distinct and often planar. Several fractures in the tail drift lie in the NE strike with vertical dip set while most formed a different set oriented N5°E to N55°NW (see Appendix C.4).

Thorpe (1984) presents the results of analyzing fracturing in borehole UG-2. General observations included a fracture frequency of 7 to 10 per meter with higher frequencies in the vicinity of fault zones. Data is presented in lower hemisphere plots and fracture frequency plots in Appendix C.4. Fracture spacing with depth agreed well with a negative exponential distribution.

Wilder and Yow (1984) conducted extensive mapping (greater than 2500 fractures) of fractures in the Climax granite. Near the SFT-C, a total of eight fracture sets were identified. The most prominent orientations (strike - dip) are N44°W - 20°NE, N24°W-vertical and N59°W-vertical. Remaining joint set orientations are N59°E-39°NW, N2°W-vertical, N82°W-vertical, N46°E-80°SE and N33°E-78°SE. Three shear sets with near vertical dip and one fault zone were also delineated. The fracture sets and their orientations corresponded well with similar fracture mapping results from other parts of the Climax Stock suggesting that the structure of the Climax is persistent over a large area. One fracture set not reported elsewhere is healed and the rock is altered suggesting that other investigations may not have included these joints in their mapping criteria. A fault zone identified in the Receiving Room was oriented N45°E to N75°SE similar to the Boundary and Shaft Station faults. This observation lead to the conclusion that a number of normal faults occur within the Climax Stock and that they are possibly related in age and genesis to the Boundary Fault (Wilder and Yow, 1984). Results of these mapping exercises are presented as equal area lower hemisphere plots, joint set orientations, rose diagrams, fence diagrams, number of fractures per borehole, fracture spacing and fracture frequency plots (see Appendix C.4).

5.5 OCRD Room - Colorado School of Mines

5.5.1 Site Description

In the summer of 1979 a room was excavated at the CSM experimental mine (the Edgar Mine in Idaho Springs, Colorado) for the installation of a thermomechanical test facility as part of an Office of Crystalline Repository Development (OCRD) program. Idaho Springs is located in the Front Range of the southern Rocky Mountain Province. Rocks at the site consist of migmatized biotite-hornblende gneiss and some granitic pegmatites belonging to the Precambrian Idaho Springs Formation. The objectives of the CSM/OCRD room are multiple and include:

1. evaluate the effect of in situ stress and stress re-distribution (resulting from storage cavity excavation) on permeability;
2. establish methodology and necessary instrumentation for performing such permeability measurements;
3. determine the extent of blast damage in rock surrounding an underground opening.

In order to achieve these objectives a number of boreholes were drilled into the rock mass surrounding the room. Seven boreholes along each of six different cross-sections (a total of 42 boreholes) were drilled in a radial pattern around the room. The boreholes were diamond drilled NX (76 mm) boreholes with cross-sections being approximately 2.4 m apart. In addition, three NX boreholes were drilled parallel to the room. A schematic of the room showing borehole locations (after Montazer and Hustrulid, 1983) is presented in Figure 5.15.

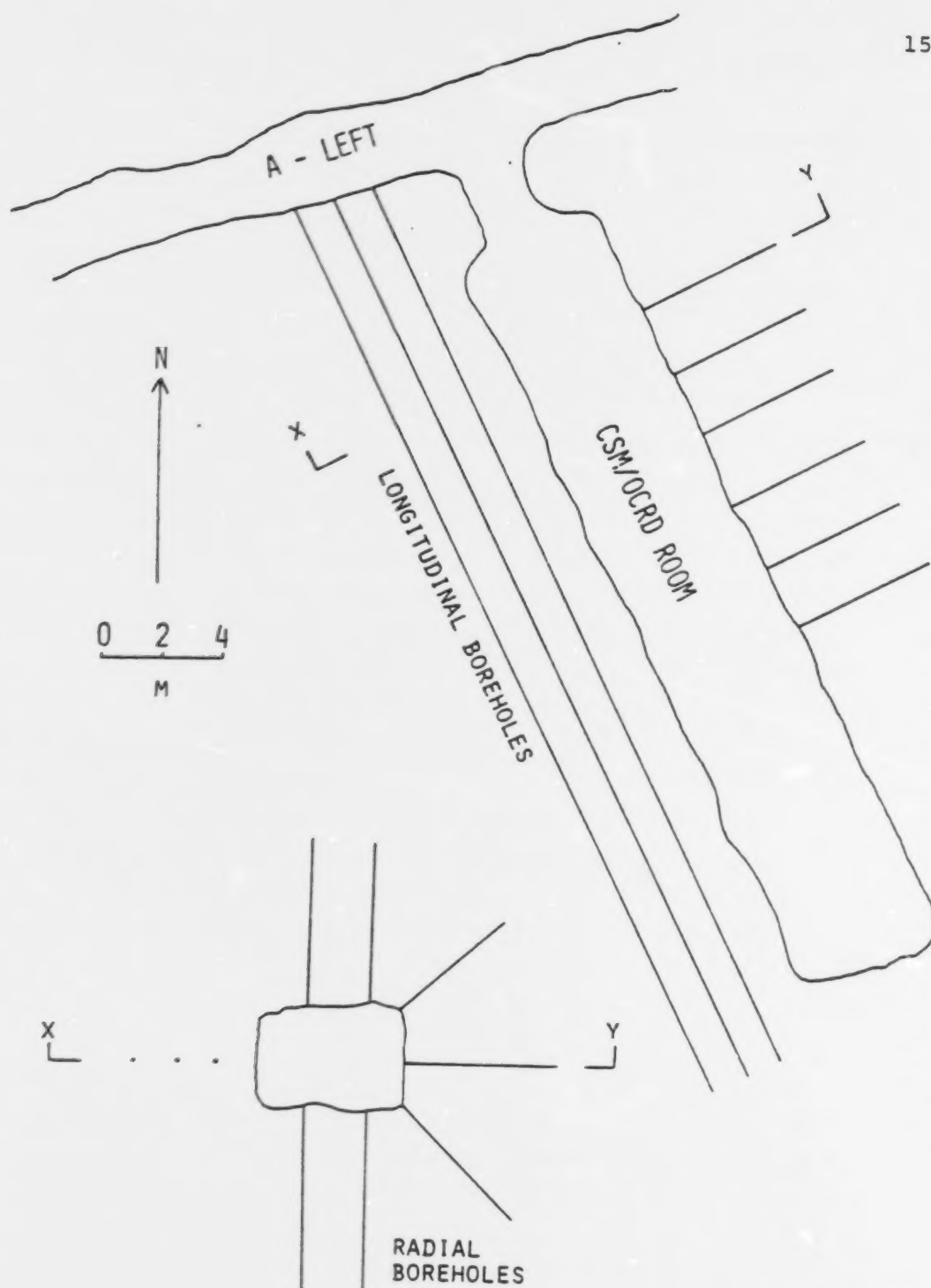


Figure 5.15 Schematic of the OCRD/CSM Experimental Room (after Montazer and Hustrulid, 1983)

Extensive investigations have been conducted in order to characterize the fracture sets and stress distribution in the vicinity of the room as well as evaluating the permeability distribution around the room. Each of these aspects of this facility are discussed in detail in subsequent sections.

5.5.2 Permeability

A number of permeability testing techniques were employed by CSM personnel to evaluate permeabilities along both the longitudinal and radial boreholes in the CSM mine adjacent to the OCRD room. These included steady-state air injection tests along with pulse testing and pressure decay tests. It is worth noting that the CSM experimental room is located in a partially saturated environment above the water table. This fact, while enabling the use of air injection techniques, does tend to complicate the analysis of the pressure response data. This is due to the fact that since the media saturation is less than 1.0 the relative permeability will not be unity. Although the precise nature of the relative permeability characteristic curve is unknown, it is fairly certain that the relationship (between relative permeability and water saturation) is highly non-linear. The highly compressive nature of air (relative to water) also further complicates the analysis.

This may partially explain the nature of some of the results obtained from the permeability testing conducted in the longitudinal boreholes. Many of the air injection tests indicate a variation of the permeability as a function of injection pressure. Montazer and Hustrulid (1983) attributed the reduction of permeability as pressure increases to the "Klinkenberg Effect" which accounts for the difference in fluid velocity at pore boundaries for gaseous (i.e., highly compressible) versus slightly compressible fluids. The

observed increase of permeability with time may be due to the two phase nature of the testing - and actually reflect the time required for water to respond to the pressure gradients. Certainly most of the data obtained by this program do not appear to be significantly different from values obtained in similar environments elsewhere. The values obtained range from a high of about 10^{-5} m/s to a low of about 10^{-11} m/s with the bulk of the values on the order of 10^{-9} m/s. Furthermore, the fact that the majority of the duplicate tests (conducted at differing pressure levels) were able to reproduce permeability values to within a factor of two to three would indicate that these results are probably at least as accurate as many other such values reported in the literature. The complete set of permeability testing results for both the longitudinal and radial boreholes are presented in Appendix A.5.

The intersection of numerous boreholes in the same fracture plane has enabled the investigators at CSM to make several observations regarding permeability variation as a function of stress and space. For example, the fracture permeability in the three longitudinal boreholes showed a significant decrease in three of five fracture zones with increasing proximity to the room perimeter. Montazer and Hustrulid (1983) suggested that this may be the result of stress-redistribution around the room (Figure 5.15) and point to the relatively high fracture permeabilities in a plane normal to the maximum principle stress as additional evidence. The permeability testing results also indicate that the fracture permeability in the radial boreholes (i.e., parallel to the axis of the room) was significantly higher than the fracture permeability in boreholes parallel to the room. Montazer and Hustrulid (1983) suggested that existing natural anisotropy of the rock may account for this finding.

5.5.3 Porosity

No references to porosity measurements for the OCRD Room were found in the literature reviewed.

5.5.4 Fracture Properties

Several studies have been performed to characterize discontinuities in the rock mass in the vicinity of the Edgar mine. Harrison and Moench (1961) (as reported by Hutchinson, 1983) completed a detailed structural analysis of the altitudes of about 6000 fractures within the CSM site. They concluded that most outcrops in the area had at least three distinct fracture sets while five or more in a single outcrop were not uncommon. The vast majority of the fracture sets could be attributed to one of several possible mechanisms including:

- the flow and subsequent cooling of Precambrian and Tertiary rocks;
- Precambrian foldings;
- the Laramide deformation of the Front Range.

Appendix C.5 contains several equal area projections of the fractures observed in surface outcrops as well as stereographic diagrams of the same outcrops.

Extensive fracture mapping has also been conducted for both the OCRD room and boreholes (as reported in Montazer and Hustrulid, 1983). Lower hemisphere equal area projections have been constructed for the continuous fractures crossing the room, fractures mapped on the faces during excavation and along the longitudinal boreholes. The dominant fracture sets have

orientations of N70°E-70°NW and N60°W-vertical with three other sets present to a lesser extent. All of this information has been reproduced and is presented in Appendix C.5. Fracture plots of sections of a wall were also constructed and are also presented in Appendix C.5. In addition, a plan view of the CSM/OCRD facility showing the results of core logging and detailed line mapping of the west wall have been included in the appendix. Findings at the site can be summarized as:

1. The rock around the room is strongly foliated with this foliation striking N70°E and dipping 70°NW;
2. A well defined fracture set is developed along the foliation;
3. Three other major fracture sets exist at the OCRD room.

5.6 Savannah River Plant Site

5.6.1 Site Description

The Savannah River Plant (SRP) is the site of a nuclear production plant owned by the United States Department of Energy (USDOE) for which E.I. Dupont de Nemours and Company are the prime contractors. At this site, deep disposal of high level liquid radioactive waste in the basement crystalline rocks below the site was proposed at one time (Christl, 1964). The USGS was consequently requested to conduct hydrologic testing at the site in conjunction with the U.S. Bureau of Mines and the U.S. Army Corps of Engineers. Hydrologic testing was conducted primarily between 1961 and 1971.

The SRP site is situated in the state of South Carolina approximately 12.5 km southeast of Augusta, Georgia (Figure 5.16). The site is adjacent to the Savannah River which forms the border between the two states. Physiographically, the SRP is located in the Atlantic Coastal Plain approximately 12.5 km southeast of the Fall Line which marks the change to the Piedmont province.

The geology at the SRP was reported (Marine, 1979) to consist of approximately 76 m of unconsolidated to semi-consolidated sediments consisting primarily of sands and clays deposited in the Cretaceous to Quaternary periods with limited Triassic sandstones (reddish brown) and shales. Below the sedimentary strata, the Precambrian crystalline rock consists primarily of chlorite-hornblende schist and hornblende gneiss with lesser amounts of quartzite. The site geology is discussed in greater detail in Christl (1964).

An extensive summary of the hydrology investigations is provided in Marine (1979) which essentially summarizes other related studies by Marine (1966; 1967) and Proctor and Marine (1965). The boreholes installed as part of these programs are shown in Figure 5.17 and are summarized in Tables 5.3 and 5.4 as follows:

DRB1-DRB7 (Marine, 1979)

- rotary drilled 3 to 61 m into crystalline rocks
- casing set and grouted to surface
- core 305 m of crystalline rock
- DRB5 and DRB7 drilled an additional 61 and 75 m respectively, prior to commencing coring
- 274 m crystalline rock penetrated in DRB5 and 305 m in DRB7

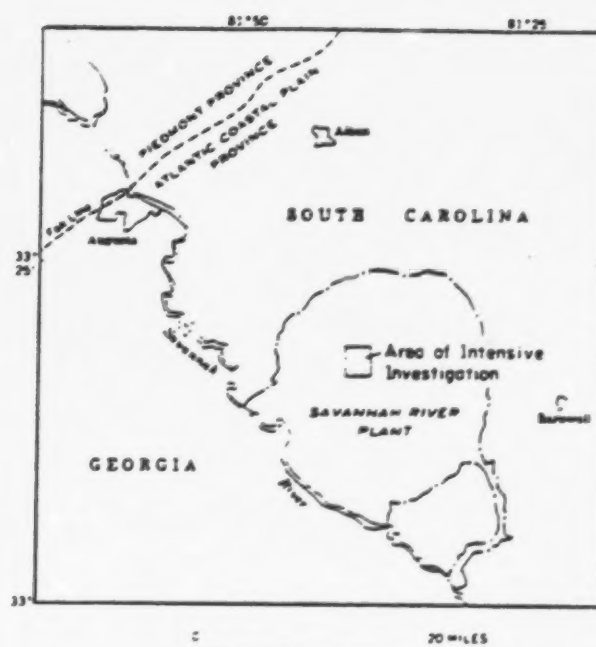


Figure 5.16: Savannah River Plant and Deep Rock Boring Area (after Marine, 1979)

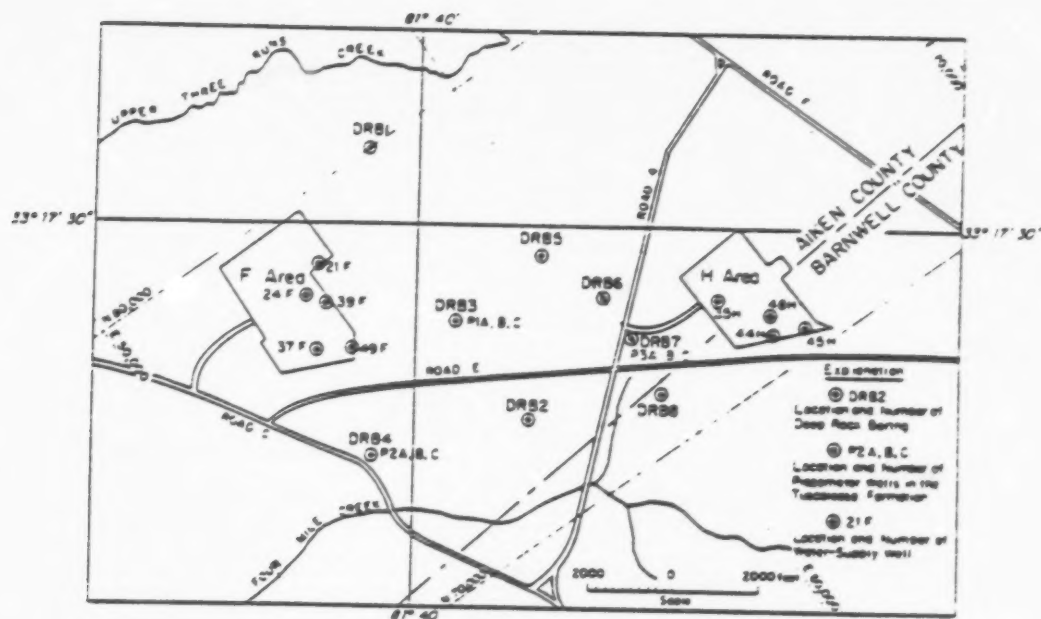


Figure 5.17 Location of Wells at the Savannah River Plant Site (Marine, 1979)

Table 5.3 Geologic and Construction Data for Wells Drilled at the Savannah River plant in 1961 to 1962 (after Marine, 1979)

Well	Altitude of Ground Surface, ft above sea level	Depth to Top of Head Aquiclud., ft	Depth to Top of Saprolite, ft	Altitude of Top of Saprolite, ft below sea level	Depth to Top of Rock, ft	Altitude of Top of Rock, ft below sea level	Thickness of Saprolite, ft	Thickness of Head Aquiclud., ft	Depth of Casing, ft	Depth at which Casing Begins, ft	Total Depth of Hole, ft	Altitude of Bottom of Hole, ft below sea level	Altitude of Top of Casing, ft above sea level
100B 1	261.6	876	884	-584	877	-615	31	51	890	890	1004	-112	262.86
100B 1P ^a													
100B 2	281.6								1210		1004		263.16
100B 3	285.5	852 ^d	860 ^d	-594	932	-600			982	982	1002	-1700	262.01
100B 3P ^b					934	-649	54	82	951	951	1042	-1656	265.20
100B 4	250.8	815 ^d	887	-616	924	-673	37	109	960	960	1088		286.80
100B 4P ^c									960		1030	-1687	252.35
100B 4P ^c									960		1557		252.85
100B 5	286.2	892	897	-605	910	-643	38	30	1754		1938		252.90
100B 6	269.8	825	890	-621	940	-671	50	187	1110	1130	1018	-1551	288.51
100B 7	277.8	899 ^d	922 ^d	-649	960	-682	33	70	1100	1100	1913	-1644	270.50
Average		858	892	-615	910	-655	40	80	1115	1160	1960	-1691	297.75
P ¹⁰	105.3	610	640 ^d	-515	620	-585	50	50	709		765	-660	106.65
P ⁵⁰	208.4		1218 ^d	-1010 ^d	1218	-1022			1253	1299	1313	-1105	209.50

a. A packer was placed at 1210 feet, and a cement plug which goes up into the casing was replaced. 100B 1P is the 1-inch pipe that goes through the packer.

b. A bridge plug was placed from 1088 to 1100 feet so that the well is effectively only 1088 feet deep.

c. A packer was placed at 1714 feet and a cement plug replaced from 1557 to 1714 feet. 100B 4P is the pipe that goes through the packer and so connects to the line from the packer to the bottom of the well. 100B 4C is the annulus between the packer pipe and the well casing, and so connects to the line from the bottom of the casing to the top of the cement plug.

d. Determined from electric log of adjacent wells in the sediments.

e. Not saprolite. Weathered Triassic red beds.

Table 5.4 Geologic and Construction Data for Rock Piezometers Drilled in Fall 1967 and Deep Rock Borings Drilled in Summer 1969 at the Savannah River Plant (after Marine, 1979)

Well	Altitude of Ground Surface, ft above sea level	Depth to Top of Saprolite, ft	Altitude of Top of Saprolite, ft below sea level	Depth to Top of Hard Rock, ft	Altitude of Top of Rock, ft below sea level	Thickness of Saprolite, ft	Depth to Bottom of Casing, ft	Cased Section, ft	Total Depth of Hole, ft	Altitude of Bottom of Hole, ft below sea level	Altitude of Top of casing, ft above sea level
P6R	253.0	745	-492	842	-589	97	852	755-861.5	1042	-789	255.91
P7R	273.0	816	-543	888	-615	72	899	755-900	1178.5	-905	275.99
P8R	357.0	766	-399	830	-473	74	829	694-833	1025.5	-668	359.60
100R B	268.6 ^d	874 ^{b,c}	-605	940 ^b	-691	86	965 ^b	840-973 ^b	1965 ^b	-1606	264.95
8 cores totaling 48 ft between 1200 and 1965 ft											
Average						82					
100R 9	302.1 ^d	between 1011 ^{b,d} and 1041	between -709 ^d and -739	1068 ^b	-766	between ^d 27 and 57	1132 ^b	930-1134 ^b	2701 ^b	-2399	295.95
5 cores totaling 128 ft between 1135 and 2649 ft											

a. Altitude of Kelly bucket on drill rig.

b. Depth below Kelly bucket which was approximately 6.8 feet above ground surface.

c. Zone of core loss, determined from electric log.

d. Not saprolite. Weathered Triassic red beds.

P1 (ABC), P2 (ABC), P3 (ABC) (Marine, 1979)

- three clusters of three wells each drilled at the site of the deep crystalline wells DRB3, DRB4 and DRB7 respectively
- A is deepest, C shallowest
- all 9 completed in Tuscaloosa Formation (coastal plain sediments)
- wells cased and grouted to surface with a 3 m long well screen

P4R, P5R (Marine, 1979)

- located remote from area of intense investigation to obtain regional hydraulic heads
- completed in upper crystalline rocks
- cased and grouted through sedimentary strata

Water Supply Wells (Marine, 1979)

- at the site of all deep rock wells and remote wells it was necessary to install water supply wells into the Tuscaloosa for use during drilling/coring
- these wells are 47 to 96 m deep with 3 m well screens

5.6.2 Permeability

Hydrologic investigations of the SRP are summarized in detail by Marine (1979) in which hydraulic conductivities are presented from lab tests, packer tests, pumping tests, two-well tracer tests and a year long pumping test. The testing was conducted primarily by the USGS during the 1960's.

Lab tests consisted of hydraulic conductivity determination for 29 cores obtained from DRB1. The method of measurement was not

reported by Marine (1979) but he did report a lower limit of detection of 3.8×10^{-13} m/s with a maximum value of 9.4×10^{-10} m/s. Approximately two thirds of the cores had hydraulic conductivities below this limit and could not be quantifiably analyzed. Of the remaining tests, the hydraulic conductivity is attributed to flow through some inhomogeneity such as fractures, infilled fractures or schist/gneiss contacts. Thus, it is somewhat unclear if these tests yield hydraulic conductivities for the matrix or are more representative of bulk values although it seems likely that they are more indicative of fracture values.

In situ testing (during 1961) initially consisted of constant head injection and withdrawal tests conducted at injection pressures of 138, 276 and 414 kPa. The analysis of these tests consisted of reporting only flowrates and not hydraulic conductivities. Also, flowrates were frequently below detection limits. Later, constant head injection tests were abandoned for slug injection and withdrawal tests.

Pumping tests (two) were conducted first in DRB3 for a period of 14.5 days (with observation at DRB1, 2 and 4) and in DRB6 for a period of 31 days (with observations in all DRB series wells) (Marine, 1979). Bulk hydraulic conductivities ranged for 2.2×10^{-7} to 6.8×10^{-7} m/s. A long term (2 year) tracer test was also conducted in a hydraulically transmissive zone between DRB5 and DRB6 and discussed in Section 5.6.3 (hydraulic conductivity of 1.7×10^{-7} m/s) (Webster et al., 1970). Further testing methodologies (discussed in Marine 1981a,b) involve utilizing a dating technique for helium in groundwater to calculate a hydraulic conductivity based on a large rock volume. Comparison of these values from different scales of testing reveal that regional hydraulic conductivities from the age of water tests were two orders of magnitude less

than values obtained from testing hydraulically transmissive zones and one order of magnitude less than lab (matrix) values. This suggests that regional flow is dominated by low hydraulic conductivity rock and that transmissive zones are not continuous at the regional scale. Also, these results were interpreted to infer that lab hydraulic conductivities provide an estimate of regional hydraulic conductivity values within one order of magnitude (Marine, 1981b).

The actual data are presented in Appendix A.6 whereas a summary of the results of the hydraulic testing at SRP is provided by Marine (1979) as follows:

- "Wells DRB2 and DRB8 have an extremely poor hydraulic connection to any of the other borings. Presumably this is because neither of these wells is deep enough to penetrate the inclined fracture zone."
- "Well DRB7 penetrates only virtually impermeable rock, but the inclined fracture zone is assumed to be only slightly below the bottom of the well, in order to explain its close hydraulic connection to DRB6."
- "Even within the fracture zones, a region of lower permeability rock exists between Wells DRB1, DRB5, DRB6, and DRB7 on the one hand, and Wells DRB2, DRB3, and DRB4 on the other."
- "Within the inclined fracture zone the region around Well DRB5 is not as permeable as the region around Well DRB6."
- "Within Well DRB5, from the bottom of the casing (1130 feet) to a depth of 1500 feet all fractures are part of

the inclined fracture zone and hydraulically connected to the fractures in Well DRB6 from 1785 feet to the bottom of the well (1910 feet)."

- "The fractures in Well DRB5 that are below 1500 feet belong to a different fracture system and are hydraulically connected to the inclined fracture zone only through the virtually impermeable rock."
- "The transmissive fractures in Well DRB8 also belong to a different system and do not connect directly to the inclined fracture zone."

5.6.3 Porosity

There are two sources of porosity data for the crystalline rock at the SRP: Webster et al. (1970) and Marine (1979). Webster et al. (1970) conducted a two well, injection/withdrawal tracer test with recirculating tracer and instantaneous tracer injection. The test was conducted in a hydraulically transmissive zone between DRB5 and DRB6 using tritium as a tracer. The two wells are separated by 538 m and the injection zone in DRB5 was isolated using packers at a depth of 257 to 370 m below sea level. The two year (739 day) test yielded hydraulic conductivities, porosities and dispersivities for the granitic rock mass at the scale of the well separation. Analysis was based on equivalent porous media concepts and yielded an effective porosity of 0.08%.

Marine (1979) also presents porosity values determined in the lab on one piece of core from each of DRB1 through DRB7. These values determined by the U.S. Army Corps of Engineers are likely indicative of matrix porosities and range in value from 0.08% to 0.19%. The method of porosity measurement used to

obtain these values was not documented in the references reviewed.

5.6.4 Fracture Properties

Fracture characteristics within single boreholes were assessed by core inspection, geophysical logs and in-hole tracer tests (Marine, 1979; 1980). It is reported (Marine, 1979) that most fractures, which at one time had been open, are now infilled by precipitation of minerals from the ground water. Isolated zones of intense fracturing which were vertically restricted but laterally extensive were observed to be the main avenues of ground water transport and were subsequently referred to as hydraulically transmissive zones by Marine (1979). One of these zones was reported to exist at the top of the crystalline rock and another occurs at an inclination of 22° southeast or more, with a strike parallel to the schistosity (strike N39°E and dip 55° southeast). Several other hydraulically transmissive zones were encountered which do not correlate at all with either of these fracture networks. Between these hydraulically transmissive zones, zones of intact crystalline rock in excess of 304 m in thickness have been encountered.

Identification of hydraulically transmissive zones was conducted either by water level response in adjacent wells during tracer tests, arrival due to pumping at a second hole or by the use of in-hole tracer tests. Core inspection proved somewhat unreliable. The use of inhole tracers is discussed in detail by Marine (1980) who noted the limited use of inhole tracers in identifying low hydraulic conductivity zones. In a modification of the technique, Marine (1980) uses a second

tracer in the borehole annulus to normalize tracer movement to reduce the uncertainty in low hydraulic conductivity zones. Hydraulically transmissive zones are superimposed on the borehole logs for each of the DRB-series wells in Appendix C.6.

Marine (1979) also attempted to correlate schistosity with the occurrence and orientation of hydraulically transmissive zones. Marine (1979) observed that 90 to 96% of fractures are either horizontal or strike parallel to the schistosity oriented at N39°E. In several wells it was observed that the same fracture could be intersected in a different borehole by following it either downdip or along the strike. As the schistosity represents planes of weakness, it is not unexpected that fracturing would develop first along these planes due to tectonic stresses. Fracture orientation data as related to schistosity is shown in Table C.6 in Appendix C.6.

5.7 Oracle Site

5.7.1 Site Description

The Oracle site, located about 8 km southeast of Oracle, Arizona, has been the site of numerous studies conducted by the University of Arizona for USNRC including Hsieh et al. (1983) and Jones et al. (1985). The studies have typically been generic in nature for the purpose of studying groundwater flow and solute transport through fractured rocks. More specifically, the work conducted at the site has focused on

techniques for evaluating fracture characteristics, geophysical properties and hydraulic properties of fractured low permeability rock, as well as evaluating the relationships that may exist between these properties.

The basement rock at the site is actually a coarse-grained biotite quartz monzonite but is commonly referred to as a granite. The batholiths comprising the Oracle granite were emplaced some 1400 Ma ago. Structurally the region has undergone several events including emplacement of diabase dikes along with related hydrothermal alteration of the adjacent granite, in the vicinity of the dikes. The Oracle granite is exposed at the north end of the Santa Catalina crystalline complex and is separated from this complex by a west-northwest trending fault known as the Mogul Fault. Another major fault system - the San Manuel Fault - is approximately 8 km northeast of the site.

Eight boreholes have been drilled at the site between February 1981 and December 1982. The boreholes range in depth from 76 to 91 m and range in diameter from 10 to 17 cm. The boreholes indicate that the soil cover at the site is approximately 2 m thick and is underlain by 10-15 m of highly weathered granite. Unweathered rock is encountered below this zone.

5.7.2 Permeability

Hsieh et al. (1983) presented the results of extensive hydraulic conductivity testing conducted in four of the boreholes (M-1, H-2, H-3 and H-4) at the Oracle site. The

program which started in September 1981, consisted of:

1. Complete hole slug tests;
2. Single hole packers tests conducted at selected intervals;
3. Cross-hole tests.

The results of the entire hole slug tests have been included in Appendix A.7. Good fits (with type curves) were reported to have been obtained for all four holes. The average hydraulic conductivity was reported as 2×10^{-8} m/s. The range of hydraulic conductivities obtained by this technique was fairly small, from 1×10^{-8} to 3×10^{-8} m/s. The results of the single hole packer injection tests is also presented in Appendix A.7. The lower measuring limit for these tests is estimated at 10^{-11} m/s (Hsieh et al., 1983). Values range from 5×10^{-11} m/s to 2.1×10^{-6} m/s. A number of the tests were subject to significant leakage past the packers. Jones et al. (1985) reviewed the data collected by Hsieh in depth. In particular, Jones et al. attempted to establish a correlation between fracture density and hydraulic conductivity. Based on core and acoustic-televviewer data the fractures were classified as either open, partly open, possibly open or closed. Jones et al. then plotted the number of fractures contained within the test interval versus the measured hydraulic conductivity for each of the aforementioned categories. Based on the results of these plots (presented in Appendix A.7) Jones et al. concluded that little if any correlation exists between fracture density and hydraulic

conductivity. Jones et al. suggest that this finding raises serious questions regarding the validity of existing conceptual models of fluid flow through fractured rock systems. While the findings of Jones et al. may indeed jeopardize existing conceptual models of groundwater flow, a number of additional factors should be considered before such a conclusion is reached. For example, the aperture size distribution and infilling material should be examined to see if they are consistent from interval to interval. A test interval containing a single wide fracture may have a higher hydraulic conductivity than a number of smaller apertures in the same size interval.

Hsieh et al. (1983) also conducted several cross-hole tests (five in total) between two wells, H-2 and H-3, at the site. The tests consisted of isolating an interval in one well (to serve as an injection interval) while a single monitoring interval was used in the observation well. Although an insufficient number of tests were conducted to evaluate all six components, Hsieh et al. were able to conclude that the tested rock mass did behave as a homogeneous anisotropic porous medium.

5.7.3 Porosity

Various techniques were employed at the Oracle site in an attempt to obtain porosity estimates. These included porosity measurements performed on cores as well as downhole neutron logs. Unfortunately the correlation between core porosities and neutron probe response was judged to be unacceptable (Jones et al. 1985). A number of reasons for the apparent lack of

correlation between the neutron log response and core measurements were speculated. Measurement scale as well as the presence of hydrous minerals were proposed as the most likely.

A third technique was also employed to obtain an in situ porosity estimate. This involved using acoustic velocity logs together with a semi-empirical relationship to relate the porosity to logging parameters. Again, the porosity values obtained from this technique were compared to those obtained from core measurements. Unfortunately, the correlation between the two methods (as presented in Figure 5.18) is poor. The reason for the poor correlation was uncertain although several causes, including rock heterogeneity, were suggested. In both cases, it can be seen that all measurements are less than 0.06 with most values being on the order of 0.02.

5.7.4 Fracture Properties

Using the results of surface mapping of rock outcrops, cores and chips obtained from various boreholes, as well as acoustic televue or logs (used to orient cores), Jones (1983) has been able to postulate the development of the fracture system of the Oracle granite. Jones suggests that the fracture system is comprised of two classifications of fracture sets, with each type being comprised of three approximately semi-orthogonal sets. The first of these classifications has been called the primary fracture set following a generic system suggested by Balk (1937). The primary system is believed to be formed subsequent to foliation and lineation and depends on the stress evolution and late emplacement history. The generic system proposed by Balk (1937) is comprised of the following mutually orthogonal sets:

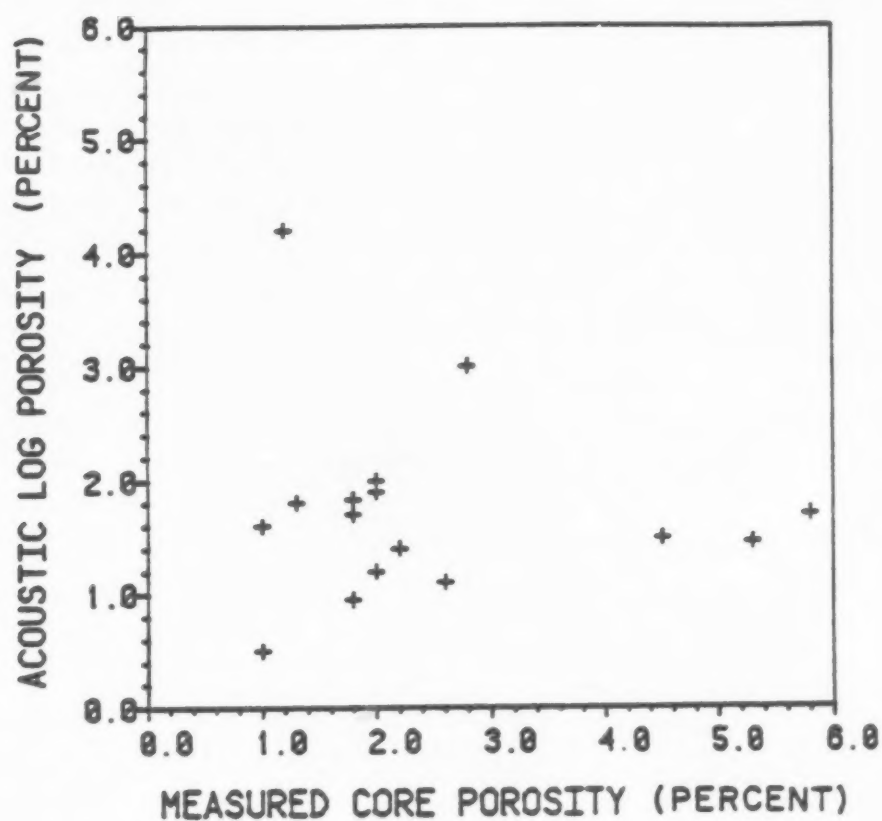


Figure 5.18 Correlation between Core and Acoustic Log Porosity (after Jones et al., 1985)

1. Cross-joints oriented perpendicular to the flow line;
2. Longitudinal joints parallel to the flow line;
3. Primary flat joints which are subparallel to the exterior boundary of the magma chamber.

Based on the three sets identified above, Jones (1983) was able to conclude that the fracture set striking approximately northwest and dipping 50° to 60° to the southwest corresponded to the cross-joint category. Another set of approximately vertical fractures striking ENE were assumed to correspond to the longitudinal set. A third set of fractures striking parallel to the dikes but dipping to the NE coincided to the flat joint classification.

In addition to the three primary fracture sets, three other fracture sets present at the site have been classified as secondary. These secondary sets are thought to result from regional tectonic events occurring after emplacement of the granite. Stereonets of surface fracture maps as well as borehole fracture maps have been included in Appendix C.7.

5.8 Basalt Waste Isolation Program

5.8.1 Site Description

The Basalt Waste Isolation Program (BWIP) was established in 1978 as part of the U.S. National Waste Terminal Storage program and is administered by Rockwell Hanford Operations. The objective of the program is to assess the potential of using basalt for long term storage of spent high level commercial radioactive waste. The BWIP site is located in the Pasco Basin of the Columbia River Plateau in Washington State (Figure 5.19). The Columbia River Plateau includes the Columbia River Basalt Group and surficial sedimentary deposits

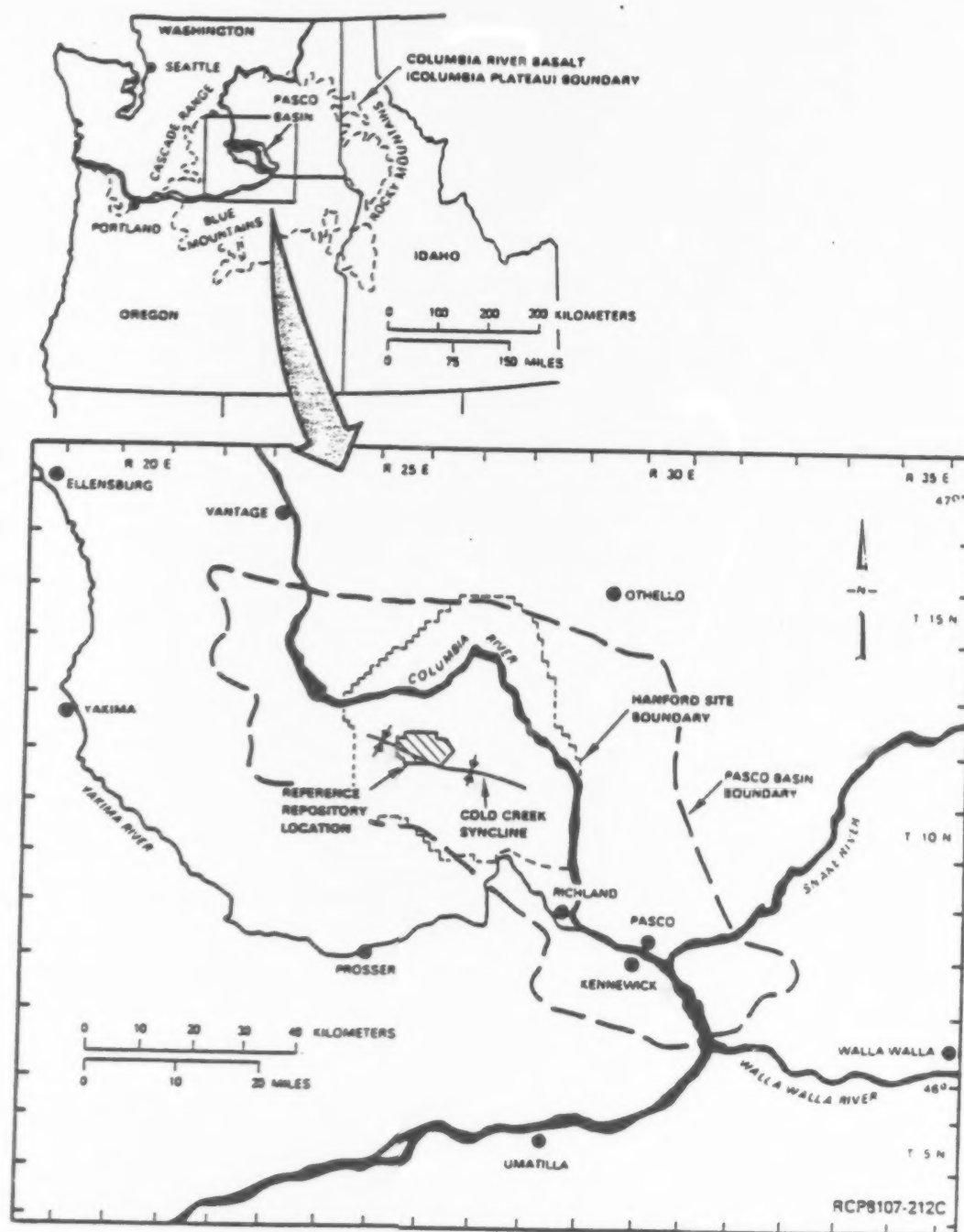


Figure 5.19 Geographic Setting of the BWIP Site (after Rockwell, 1982)

derived from the local Hanford and Ringold Formations in the Pasco Basin (Rockwell, 1982). The site itself is located in the central portion of the east-west trending Cold Creek Syncline. This is the most prominent land form in the area and is due to folding of the thick basalts. The basalts which outcrop in this basin as part of the Columbia River Basalt Group include the Saddle Mountain, Wanapum and Grande Ronde Basalts. These basalts are a series of permeable basalt flow tops and interflow horizons interspaced amongst low permeable zones of intact basalt. The cumulative thickness of the basalts is in excess of 3000 m (Gephart et al., 1983). At the bottom of the flow, a thin zone (0.5 m) of fractured, glassy basalt with alteration is often encountered depending on whether shallow or deep water was present during rock cooling (Gephart et al., 1983). The interior zones range in thickness from a few meters to 100 m (Rockwell, 1982) with most fracturing attributed to thermal contraction during cooling. The flow tops and interflows consist of a vesicular and/or brecciated basalt comprising, on the average, 15% of the flow thickness. Gephart et al. (1983), Deju (1977) and Rockwell (1982) provide detailed descriptions of the area geology.

The candidate horizons for the repository lie between 870 and 1100 m below ground surface in the Grande Ronde Basalt (Gephart et al., 1983) within a thick basalt flow interior. At this depth the potential repository would be overlain by approximately 700 m of layered basalt. The general approach to field characterization of the basalt at BWIP is discussed briefly by Leonart et al. (1985) and involves four main areas, as follows:

- reconnaissance investigations;
- hydraulic head baselining;
- large-scale hydraulic testing;
- underground tests.

An extensive hydrologic test program is underway at the BWIP site for which the test site locations are shown in Figure 5.20.

Rockwell (1982) provided a broad in depth coverage of site characterization activities to 1982 including site instrumentation and the hydrologic program.

5.8.2 Permeability

Several different organizations (Table 5.5) have been involved in hydrologic site characterization of the BWIP site. Rockwell (1982) and Gephart et al. (1979) present extensive documentation of hydrologic properties measured at the site. Hydrologic testing conducted at the BWIP has included constant discharge, constant drawdown, displacement, constant-head injection, water potential and tracer tests according to Rockwell (1982). These tests were generally single or double packer tests, single packers being used during drilling.

Up to 1982, the emphasis of the hydraulic testing program within the basalt was on testing of the more permeable flow tops and interbeds to depths of 1500 m (hydraulic conductivities of 2×10^{-10} to 1×10^{-5} m/s) (Rockwell, 1982). Since then, more emphasis has been placed on hydraulic testing of the interior basalt flows such as the work of Spane and Thorne (1985) who found hydraulic conductivities in the 10^{-11} to 10^{-13} m/s range.

Rockwell (1982) presented the results of a wide variety of hydraulic testing programs at the BWIP. The main form of this data consists of plots of hydraulic conductivity versus depth

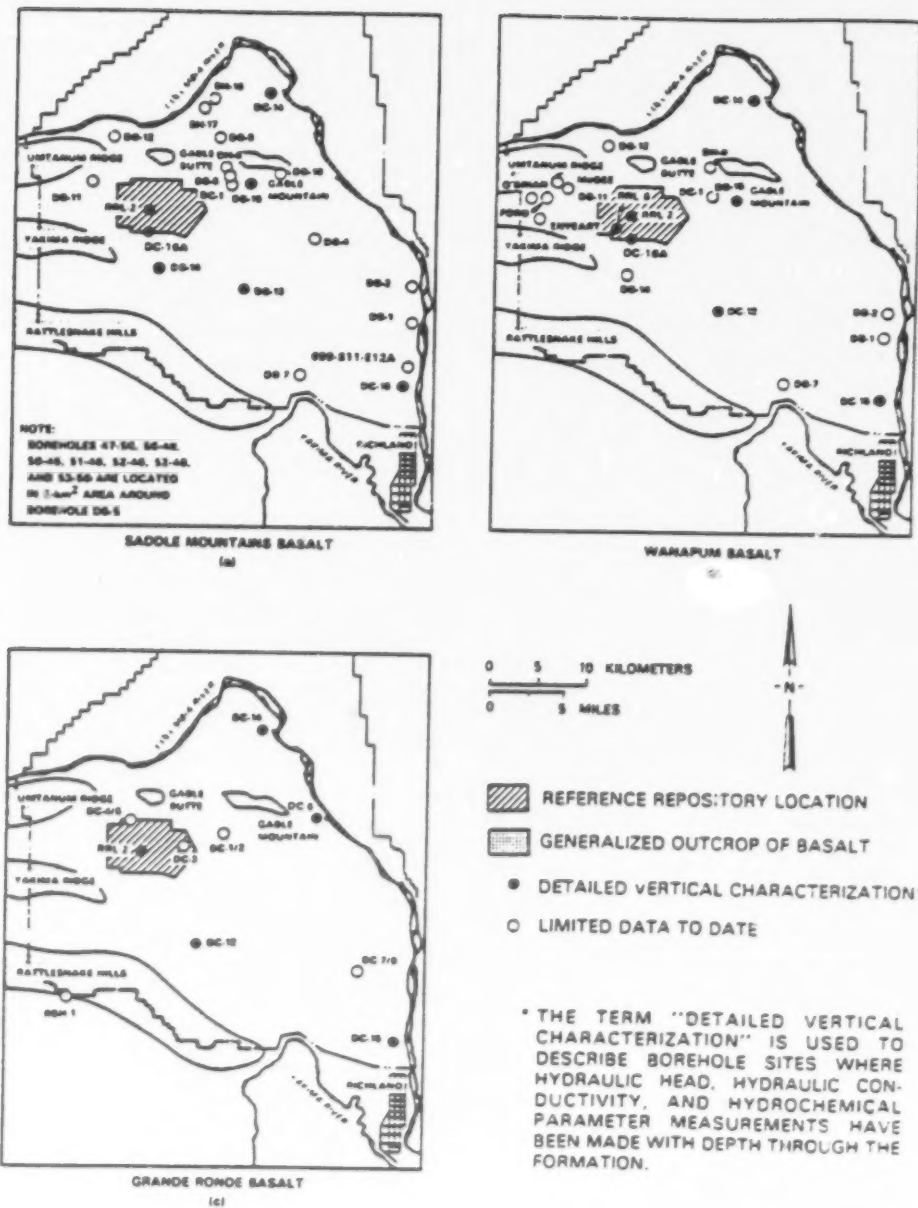


Figure 5.20 Hydrologic Test Site for Individual Formations within the Columbia River Basalt Group (Rockwell, 1982)

Table 5.5 Principle Groups Involved in the BWIP Hydrologic Testing Program (after Marine, 1979)

Date	Group	Borehole*	Work accomplished	Basalt formation
1968	Raymond and Tillson (1968), Battelle, Pacific Northwest Laboratories	RSH-1	7 drill stem tests, 7 head measurements	Grande Ronde
1969	LaSala and Doty (1971), U.S. Geological Survey	DC-1	4 pumping tests, 11 fluid injection and withdrawal tests, 22 head measurements, water samples	Saddle Mountains, Wanapum, and Grande Ronde
1977	Gephart et al. (1979b), Rockwell Hanford Operations	RSH-1	7 withdrawal and injection tests, water samples	Grande Ronde
1978	SAI (1978), Science Applications, Inc.	DC-2	6 injection tests, 2 head measurements	Grande Ronde
1978	Apps et al. (1979), Lawrence Berkeley Laboratory	DC-2	6 head measurements, 1 water sample	Grande Ronde
		DC-6	15 head measurements, 12 flow tests, 1 water sample	Grande Ronde
		DC-8	4 head measurements	Wanapum
1978	W. K. Summers and Associates	8 springs	8 water samples	Saddle Mountains and Wanapum
1978-79	Rockwell Hanford Operations	DB-1, -2, -4, -5, -7, -9, -10, -11, -12, -13, -14; DN-8; and WPPSS-3	20 head measurements, 12 pump tests, 10 water samples	Saddle Mountains and Wanapum
		4 irrigation wells in Cold Creek Valley area	4 head measurements, 1 pump test, 4 water samples	Wanapum
1980-82	Rockwell Hanford Operations	DB-1, -2, -4, -5, -7, -9, -10, -11, -12, -13, -14, -15; DC-3, -6, -7, -8, -12, -14, -15, -16A; DN-8; 699-S11-E12A; 8H-16; RRL-2, -6; 47-50, 50-45, 50-48, 51-46, 52-46, 52-48, 53-50; 4 irrigation wells; and 15 springs	Approximately 145 separate intervals in the noted boreholes have had constant discharge, constant drawdown, displacement, constant head injection tests, water samples, and/or head measurements made.	Saddle Mountains, Wanapum, and Grande Ronde

*Boreholes in which hydrologic tests have been conducted.

for a specific borehole. The test interval length is also indicated (see Appendix A.8). Although this is an excellent summary document, little information is available on the source of the data such as test and analysis method, test zone lengths and pressures. Some discussion exists on test method determination as a function of anticipated hydraulic conductivity from rock cores, temperature, resistivity/self potential, natural gamma, gamma-gamma, sonic, caliper and neutron logs. Tracer testing between boreholes DC-7 and DC-8 is also discussed but no hydraulic conductivity or porosity values were calculated for this test (only transmissivity and storativity) due to uncertainty in the thickness of the transmissive zones (Rockwell, 1982).

More recently, Gephart et al. (1983) and Spane and Thorne (1985) have presented the results of hydraulic testing in basalt flow interiors. Gephart et al. (1983) conducted pulse and constant head injection tests at depths of 350 to 1200 m and generally found a horizontal hydraulic conductivity for the colonnade and entablature basalt of less than 10^{-11} m/s. This study also discussed various conceptualizations of groundwater flow in the BWIP area. Spane and Thorne (1983) measured bulk hydraulic conductivities ranging from 3.5×10^{-12} to 2.4×10^{-11} m/s.

Spane and Thorne (1985) conducted over-pressure pulse tests (pulse injection tests) and multi-step (four) constant head injection tests. The main objective of these tests was to evaluate the formation hydraulic parameters prior to (Phase I) and following (Phase II) introduction of bentonite based drilling fluid into an interval of the formation which had previously only been exposed to fresh drill water. These tests were performed in a 24.7 m interval in borehole DB-2 between the 363.4 and 288.1 m depths in a basalt flow interior. Both

transient and steady state analyses were performed from the injection test data.

Phase I testing was conducted at over-pressure values of 196.29 to 333.31 kPa for the pulse tests and constant head injection tests were performed at four pressure increments resulting in stresses between 115.03 and 337.59 kPa. Phase II testing was conducted under similar conditions. A comparison of values between the two phases (see figure in Appendix A.8) shows comparable estimates of hydraulic parameters for each of the phases. Pressure pulse tests consistently resulted in greater variability and lower hydraulic conductivities than injection tests. Hydraulic conductivities from constant head injection tests were nearly identical between the phases with transient analyses resulting in values within a factor of two of steady state analyses. No discernable relationship between hydraulic conductivity and stress was evident and skin factors suggested that well conditions varied from slightly impaired (positive skin) to slightly stimulated (negative skin). Overall, the measured hydraulic conductivities (Table A.8, Appendix A.8) showed no discernible influence on hydraulic properties due to the use of bentonite in the drilling fluid.

5.8.3 Porosity

No porosity values were encountered for the BWIP basalts as part of the literature review of the BWIP site characterization studies. Tracer tests discussed in Rockwell (1982) do not yield porosity values due to the uncertainty in the length of the contributing zone length. Gephart et al. (1983) estimated that less than 0.4% of the rock volume consists of unfilled fracture, particularly in the Grande Ronde Basalt. This value may be indicative of fracture porosity at the BWIP site.

5.8.4 Fracture Properties

Fracture characteristic data for the BWIP site were found to be relatively limited. Gephart et al. (1983) observed fracture frequencies of one to 30 fractures per meter and apertures typically less than 0.5 mm which were usually filled with secondary minerals. Gephart et al. (1983) estimate that less than 0.4% of the rock volume consists of unfilled fractures, particularly in the Grande Ronde Basalt. Some fracture orientation values from Rockwell (1982) are presented in the appendices (see Table D-9, Appendix D.9).

5.9 AECL's Underground Research Laboratory

5.9.1 Site Description

Atomic Energy of Canada Limited's (AECL) Underground Research Laboratory (URL) (Figure 5.21) is located approximately 12 km east of the town of Lac du Bonnet and approximately 13 km northeast of AECL's Whiteshell Nuclear Research Establishment in southeastern Manitoba. The site covers an area of 3.9 km² and is accessible from Manitoba Provincial Road 313.

The site is located within the Lac du Bonnet Batholith, one of several acidic plutonic bodies in the Wanipigow - Winnipeg Rivers region in southeastern Manitoba and within the English River subprovince of the Superior Province of the Canadian Shield (Betcher et al., 1981). The batholith dimensions are approximately 80 km by 25 km.

Geologically, the pluton is composed of several intrusive phases of granitic rock. Stone et al. (1984) has divided the lithology into five units (1) pink porphyritic granite (2) foliated pink granite (3) grey granite/quartz monzonite

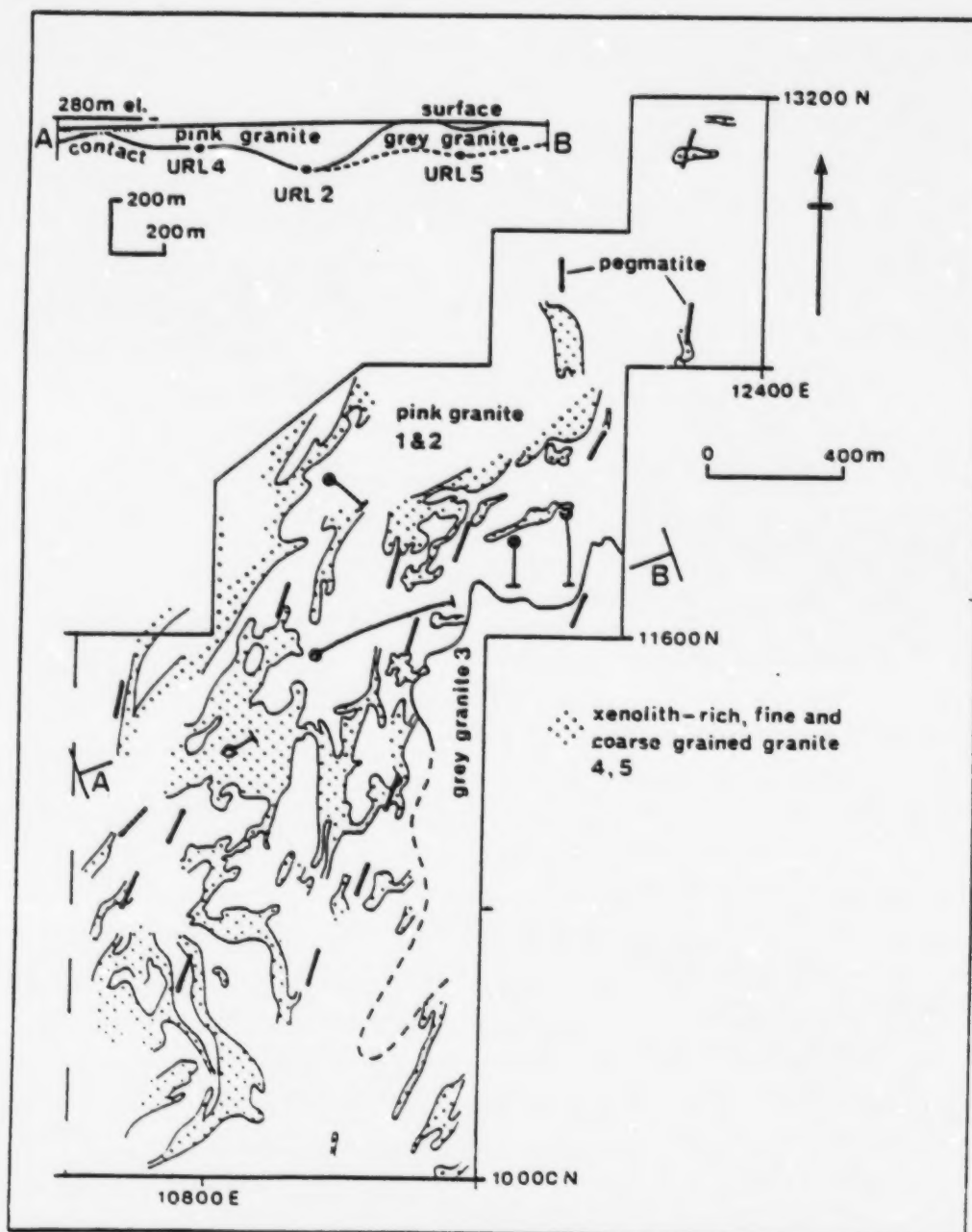


Figure 5.21 Geologic Map and Cross Section of AECL's Underground Research Laboratory (from Brown, 1982)

(4) xenolithic granite (5) pink fine and coarse grained granite. The lithologic units are cut by high temperature pegmatite and aplite dykes which preferentially strike north-northeast. The area is also traversed by younger fractures of various strikes with either shallow or steep dips (moderately dipping fractures are rare).

The research objectives of the URL are (Mayman (1980)):

- (1) test the capabilities of the surface geological and geophysical techniques to locate structural or lithological discontinuities at depth;
- (2) determine the hydrogeological conditions in the area and monitor perturbations in the conditions caused by construction;
- (3) obtain a three-dimensional picture of the tectonic structure and stress conditions in the area.

To date, extensive geologic mapping (Stone et al., 1984; Brown, 1982; Tammemagi et al., 1980) and geophysical surveying (Soonawala, 1982) have been completed at the site. Fracture characteristic were mapped on surface and in boreholes. Groundwater monitoring networks consisting of at least 54 overburden piezometers, 39 bedrock piezometers, 14 multilevel piezometers or nests, and 11 core holes (installed with multilevel casing), provide hydrogeologic and geochemical data.

Background hydrogeologic data from numerous borehole hydraulic and pump tests and long term water level monitoring have established formation hydraulic conductivity and hydraulic head distributions. Three extensive subhorizontal

hydraulically-continuous fractures zones were identified at depths of about 100, 300 and 400 m below ground surface (Davison, 1984; Davison and Guvanasen, 1985). Hydrogeochemical data was used to assist in distinguishing the fracture zones and to characterize the variation of the groundwaters within the rock mass.

Based on calibration to the background hydrogeologic data numerical groundwater flow models were used to describe the groundwater system and to predict the hydrogeologic drawdown caused by the excavation of the shaft of the URL (Guvanasen, 1984; INTERA, 1984). Upon construction of the shaft monitoring of the hydrogeologic response was initiated and will continue until completion of the shaft (scheduled as mid-1986). Records were kept of the water inflow into the shaft.

5.9.2 Permeability

In situ permeabilities of the granite at the URL site range from 10^{-14} to 10^{-4} m/s (Davison, 1982; Davison et al., 1982a) as measured by straddle packer tests with intervals that range from meters to 100's of meters. High permeabilities are associated with three highly fractured areas in easterly dipping zones at roughly 100, 300 and 400 m below surface. One fracture zone (Number 2) was studied in detail (Davison, 1984, 1985) by large scale hydraulic responses (pump) tests. Several very high and high permeability areas ($\sim 10^{-4}$ m/s), oriented approximately north-south and east-west are contained in the zone. Low permeability ($\sim 10^{-10}$ m/s) areas are also found in the same fracture zone. Bulk rock permeabilities are demonstrated by results from testing of long borehole intervals (e.g., ~ 100 m) and range from 10^{-14} to 10^{-12} m/s.

The variation of in situ permeability with depth appears to be dependent on intersection with and position of fracture zones within the rock mass. Relatively intact rock (low permeability) is found between the fracture zones (high permeability). Fracture zones were not detected below about 450 m below surface. A shallow (< 100 m depth) fracture zone illustrated that the permeability is anisotropically distributed with higher permeability along the strike rather than down dip. A deeper fracture zone (Number 2 @ 100-300 m) is more complex with a great deal of spatial variation in the permeability of the zone and distinctive channels of extremely high permeability generally oriented north-south and east-west.

Complete data results of hydraulic conductivity values from the Underground Research Laboratory are provided in Appendix A.9.

5.9.3 Porosity

Porosity values for the plutonic rocks in the area of the Underground Research Laboratory have not been reported in the literature, however, samples of the Lac du Bonnet Batholith from the Whiteshell Research area are likely to be similar. Values collected from Whiteshell boreholes are reported in Section 5.12.13.

5.9.4 Fracture Properties

Fracture characteristics for the granitic rocks of the Underground Research Laboratory have been measured by Stone et al. (1984) and Brown (1982) and have been noted to fall into two sets; one set consisting of shallow dip (less than 30°) fractures and the other set consisting of steep dip (greater than 60°) fractures. Fractures with moderate dips are rare.

Shallow-dip fractures for the entire URL site have a preference to strike east-northeast. The average length and spacing of the subhorizontal fractures are 17.5 and 1.8 m, respectively.

Steep-dip fractures are more complex. Two orthogonal subvertical fracture sets at 030° and 120° are the commonest subvertical sets and are reported to be extensional in origin (Brown, 1981). A third set is oriented south-southeast but is not found in all the subareas. The mean length of the steep-dip fractures is 14 m and spacing varies between 5 and 22 m.

These fracture sets are present throughout the URL lease but undergo changes in orientation and abundance. Variations in fracture abundance appears to be related to rock type although all granitic phases are fractured to some extent.

The fracture sets likely formed as the rocks cooled and before the batholith completely solidified. The oldest fractures are filled with residual magma (pegmatite and aplite). Fracture sets resulted from both shear (east-northeast shallow-dip set) and extension (030° and 120° steep-dip set) of the rock mass.

5.10 AECL's Atikokan Research Area

5.10.1 Site Description

AECL's Atikokan Research Area (Figure 5.22), located about 200 km west of Thunder Bay, Ontario, is within the Eye-Dashwa granitic pluton. The pluton is elliptical in shape and is composed primarily of coarse-grained hornblende-biotite granite (Brown et al., 1980).

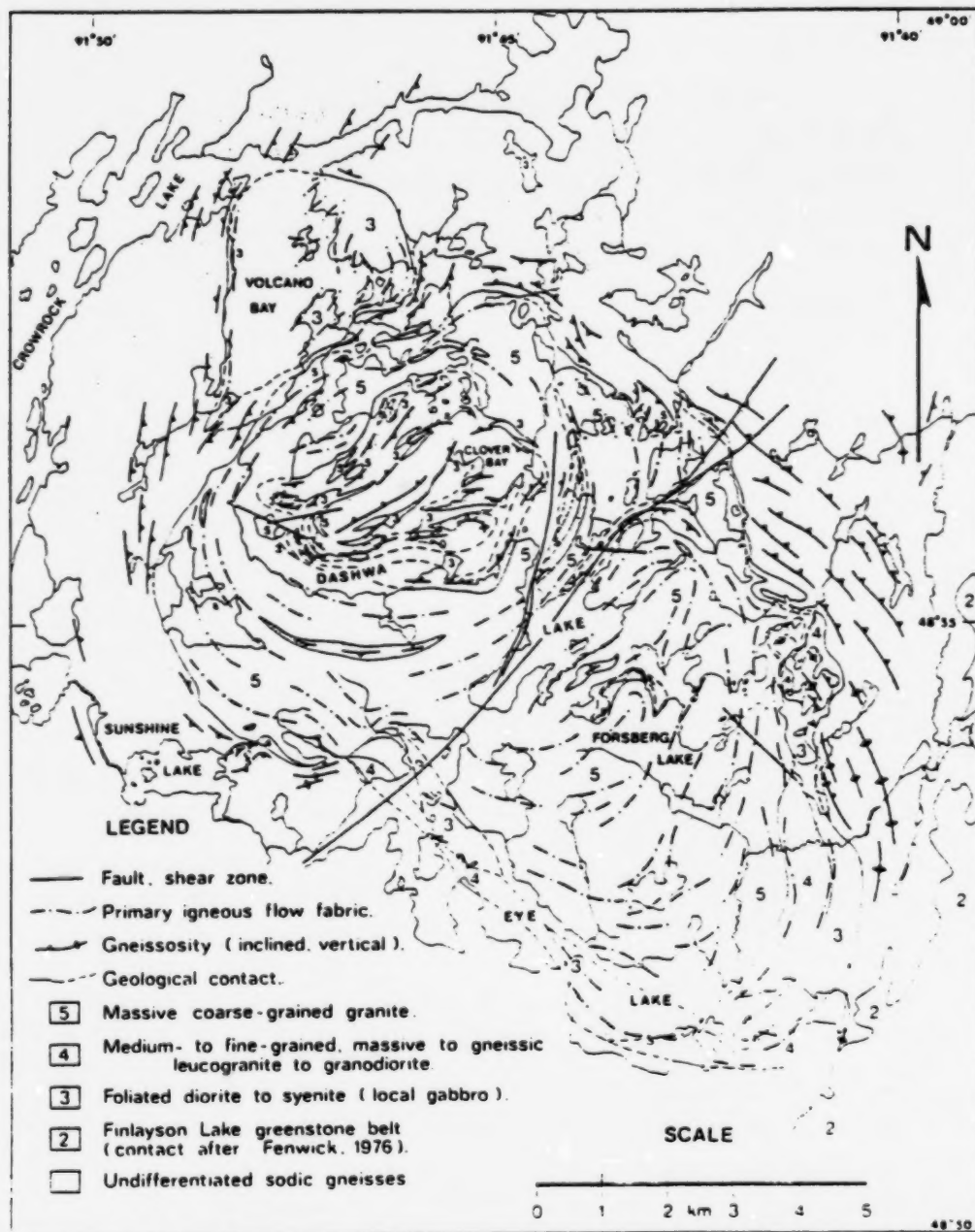


Figure 5.22 Geological Map of the Eye-Dashwa Pluton, Atikokan, Ontario (Brown et al., 1981)

The general geology of the site as interpreted by Brown et al. (1980) and Brown et al. (1982a,b) places the pluton as a post-tectonic granite body which was intruded into the crust approximately 2500 Ma ago, following the deformation and metamorphism which affected the surrounding gneisses and volcanic rocks (Schwerdtner, 1977; Simpson, 1977). Regional stress fields after the deformation and metamorphism resulted in fracturing of the rock mass. The pluton is surrounded by Dashwa Gneiss, a tonalitic to amphibolitic gneiss complex (Brown et al., 1980).

Like the other AECL research areas, considerable effort has been extended to characterize the geologic setting, fracture characteristics, hydrogeology and geochemistry of the Eye-Dashwa pluton. A brief summary of the major studies include:

- Geologic Studies - The tectonic history and geologic setting has been defined by Brown et al. (1980) for the purpose of defining the pluton's shape and bulk characteristics. The grain size and mineralogy of rocks at the margins, density, strength, permeability, and thermal properties were described by Kamineni and Brown (1981), Drury (1981) and Chernis (1982).
- Geophysical Surveys - Airborne, ground, and borehole surveys such as airborne magnetic, electromagnetic, magnetotellurics, resistivity and very low frequency electromagnetic surveys identified lineament related anomalies.
- Fracture Characteristics - Regional, detailed and grid fracture surveys (Stone, 1980) and borehole logging (T.V. camera, acoustic televiewer etc. (Hillary, 1982b)

characterized the surface and subsurface fracture characteristics. Work with Ontario Hydro provides fracture characteristics from an adjacent intake tunnel and a dewatered lake bottom (Pearson, 1982). Studies have identified, in the subsurface, two easterly dipping fracture zones extending to surface in the grid area (Stone, 1980).

- Hydrogeologic Studies - Phases of hydrogeological testing included (Pearson, 1982; Hillary, 1982): reconnaissance logging of hydraulic conductivity and hydraulic head for specific intervals, groundwater sampling for general water quality, and hydraulic continuity testing.

Studies at Atikokan were limited so that AECL personnel and resources could be devoted to the URL and Eastbull Lake Research Areas.

5.10.2 Permeability

Permeability measurements at Atikokan were completed in several boreholes set in granite but only limited results have been found in the reviewed literature (results are referenced as in preparation but were never published in the AECL's Technical Record series). Limited results are presented by Pearson (1982), Stone (1981) and Hillary (1982a,b) but the test methods are not described.

Hydraulic conductivities range from 10^{-12} to 10^{-6} m/s in the granitic Eye-Dashwa Pluton. There is a general trend to lower permeabilities with depth. The near surface has values in the range of 10^{-7} to 10^{-6} m/s. The higher permeability zones are found in narrow zones of high fracture

frequency (Hillary, 1982a,b). Limited testing results for the Atikokan Research Area are found in A.10.

5.10.3 Porosity

Porosity values for the Atikokan Research area have been determined by Drury (1981) and, to some extent, Chernis (1984). Values for matrix porosities range from 0.003 to 0.010 cc/gm for granite and granodiorite using a point count method on core samples (Drury, 1981) and generally decrease with depth. Chernis (1984) essentially confirms this result.

5.10.4 Fracture Properties

Fracture characteristics in the area of AECL's Atikokan Research area have been analyzed by Brown et al. (1980), Stone (1980) and Hillary (1982b). The fractures of the Eye-Dashwa granitic pluton are not randomly distributed but occur in oriented sets in both the pluton and surrounding gneissic rocks. Variations in the orientation of the sets are found with position in the pluton.

Stone (1980) reports the following are the dominant fracture sets from surface mapping. The regional and detail areas contain three preferred orientations consisting of east-striking vertical fractures, north-striking vertical fractures and northeasterly striking fractures with moderate northerly dip. The grid area is different with most fractures striking southeasterly with a vertical dip. Fracture types were used to further classify set orientations. Left hand faults (visible displacement) have preferred strikes of 176°, 5° and 157° for the regional, detail and grid areas respectively while right hand faults have preferred strikes of 87°, 67° and 125° for the same areas. Strikes of moderately-dipping, non-faulted, non-

filled fractures are 34°, 37° and 70° for regional, detail and grid areas, again showing the local variation found in the small scale study. Filled fractures have strikes with a unimodal distribution with a mean of 75°.

For all fractures combined, frequencies of 1 to 1.5 fractures per meter were reported (Stone, 1980). Fracture lengths for the regional and detail areas were similar at 1.85 and 1.65 m while the grid area has a higher average length of 4.05 m.

In boreholes at Atikokan, fracture families were identified by Hillary (1982b) in several zones of high fracturing. Three main fracture sets were found to dominate the subsurface in the Atikokan boreholes. One set is visible on surface as a 1 km long lineament trending north-northwest that extends at least 1 km in depth. It is made up of a series of subparallel steeply dipping fractures. A second subhorizontal set is dominant within 200 m of surface but is also found at depth. The third set trends southwest with a moderate dip. Complete fracture data for Atikokan is given in Appendix C.10.

5.11 Chalk River Research Area

5.11.1 Site Description

AECL's Research Area 2, Chalk River Nuclear Laboratories (CRNL) (Figure 5.23) located on the Ottawa River approximately 200 km northwest of Ottawa, Ontario, has been used for crystalline rock research since about 1977. Study areas are found in the outer reaches of the plant site property.

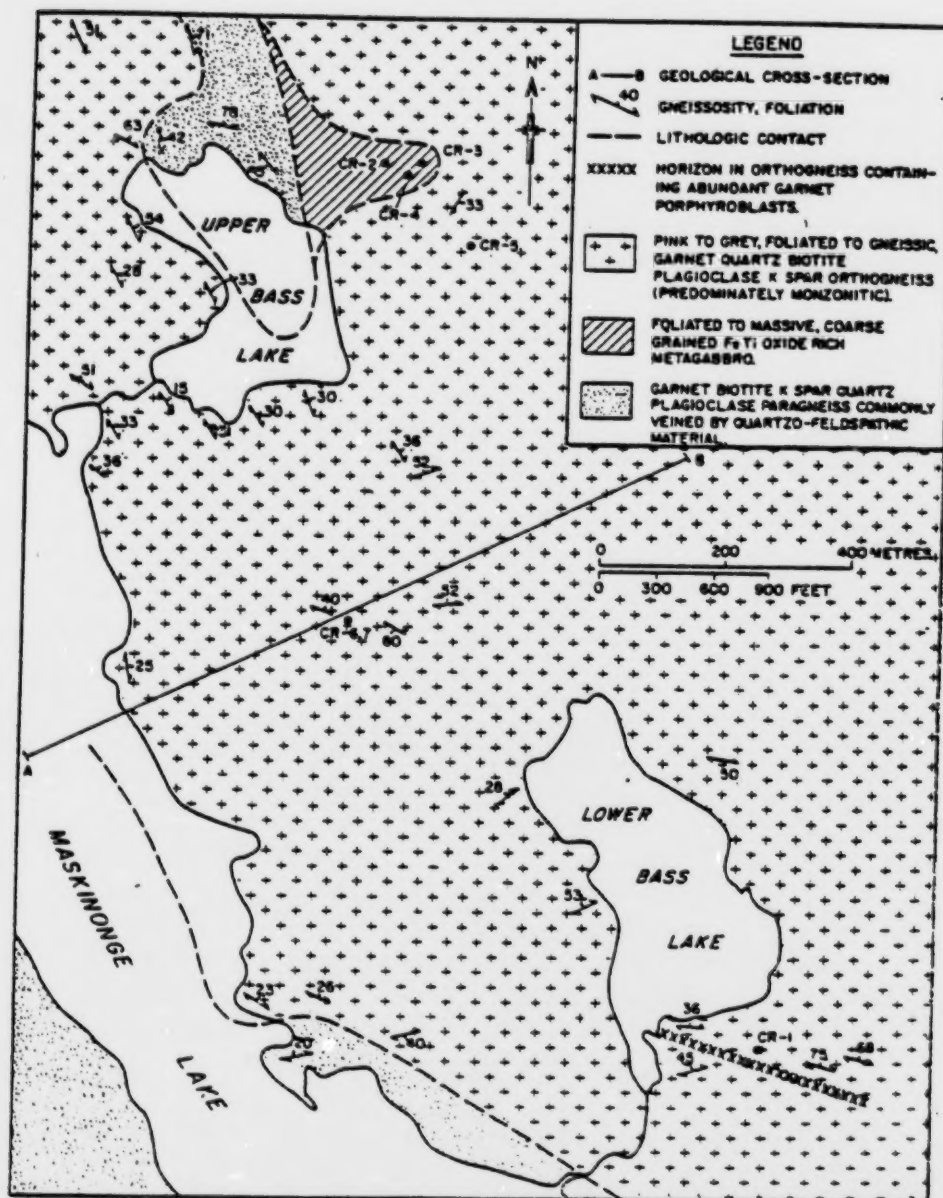


Figure 5.23 Geological Map of the Chalk River Research Area (Raven, 1980)

The Chalk River area forms part of a gneissic granitoid terrain which was intensely deformed and metamorphosed during the Grenvillian Orogeny approximately 950 Ma ago (Bourne and Rey, 1976). Subsequent to experiencing high grade deformation and metamorphism the area was extensively faulted and fractured by fault movement related to the initiation and continued subsequent activity of the Ottawa-Bonnechere Graben (Brown et al., 1981a,b). The area is known to be seismically active and may still be tectonically active.

Considerable research has been conducted at Chalk River in the last ten years with regard to determining the geologic and hydrogeologic nature of the bedrock. A brief summary of the research programs conducted at Chalk River include:

- Geological Studies - Mapping of regional bedrock geology from surface outcrop and numerous boreholes has been conducted (Lumbers, 1972; Bourne and Rey, 1976). The tectonic setting in relationship to the Ottawa-Bonnechere Graben (Brown et al., 1982a) has been identified.
- Fracture Studies - Detailed fracture characteristics from airphoto analysis, outcrop mapping and borehole logging have been studied by Raven (1980), Brown et al. (1982a,b), and Raven (1985).
- Geophysical Studies - Airborne, ground and borehole geophysical surveys have all been applied to studies of the bedrock in the Chalk River area primarily by various members of the Geologic Survey of Canada.
- Hydrogeologic Studies - Hydraulic testing and water level monitoring of borehole intervals have provided

detailed characterization of hydraulic conductivity and hydraulic head for selected areas of the research site (Davison, 1980; Raven, 1985). Cross-hole interference testing, large scale pump tests and double and multiple hole tracer tests have also been conducted (Davison, 1981; Raven et al., 1984; Novakowski et al., 1983). A flow system study to identify the characteristics of a fractured crystalline rock mass has been completed by Raven (1984).

- Geochemical Studies - The chemistry and isotope geochemistry of the groundwater were characterized by Bottomley et al. (1984).

5.11.2 Permeability

Permeability measurements at CRNL were determined by Raven (1980), Davison (1981) and Raven (1985) for a number of different locations in granitic and monzonitic gneiss. Hydraulic conductivities range from about 10^{-12} to 10^{-4} m/s. Raven's (1980) test results were obtained from pulse injection/withdrawal and constant head injection tests. Davison (1981) used constant head injection, pressure pulse injection and cross-hole interference (by constant head injection) tests in primarily two boreholes (CR6 and CR7) of less than 300 m depth.

The flow system study conducted by Raven (1985) used 17 boreholes of various depths less than 60 m to characterize the hydraulic conductivity of a small volume of rock mass. Straddle packer injection tests and hydraulic interference tests (constant discharge and constant drawdown) yielded hydraulic conductivities in the range of 10^{-12} to 10^{-4} m/s for the rock mass. Four fracture zones or large

single fractures continuous over 50 m were identified. A mean hydraulic conductivity 2×10^{-9} m/s was calculated for the site based on over 350 injection tests. Nineteen hydraulic interference tests using various activation and monitoring boreholes resulted in the determination of an average radial and vertical hydraulic conductivity in the range of 5×10^{-7} to 3×10^{-6} m/s using the Gringarten (1982) model. The calculated hydraulic conductivities indicate enhanced vertical permeability relative to radial permeability by factors of 10 to 170 in Fracture Zone 1. Equivalent single fracture apertures calculated from transmissivities ranged from 45 to 900, 13 to 355, 13 to 240 and 60 to 63 μm for Fracture Zones 1, 2, 3 and 4 respectively.

In boreholes CR6 and 7 hydraulic conductivities were generally lower at depth but the shallow nature of these holes does not confirm that permeability decreases with depth. At the flow study site boreholes less than 60 m deep do not provide an adequate data base to determine the permeability distribution with depth.

Laboratory studies by Cooley and Butters (1979) determined the permeability of core samples from boreholes CR6 and 7. Their results are as follows: CR6 - 4.8×10^{-13} to 1.2×10^{-12} m/s and CR7 - 4.8×10^{-13} to 1.7×10^{-12} m/s for samples at ambient pressure; and CR6 - 4.8×10^{-13} to 1.5×10^{-12} m/s and CR7 - 4.8×10^{-13} to 7.8×10^{-12} m/s for samples at in situ pressures. Cooley and Butters (1979) also found that permeability decreased with increasing effective stress, increased with temperatures above 75°C and was independent of pressure pulses up to 16% of the pore fluid pressure.

5.11.3 Porosity

Wadden (1979) determined porosity of core samples of Chalk River gneisses using an immersion technique. Values of repeated measurements for one depth (227 m) range from 0.0030 to 0.0048 cc/gm with an average matrix porosity of 0.0034 cc/gm and a precision of 9%. Over a range of depths of 10 to 300 m the matrix porosity varies from 0.00098 to 0.047 cc/gm (Wadden, 1979) and in general do not show a decreasing trend with depth. Radwan (1979) determined similar values in the range of 0.0018 to 0.0037 ml/ml using the same techniques. Drury (1981) found similar results with a range of 0.002 to 0.026. These results can be considered representative of the gabbro, granitic gneiss and monzonitic gneiss found at Chalk River.

5.11.4 Fracture Properties

Fracture characteristics of the metagabbro, gneiss and monzonitic gneiss of the Chalk River Research Area have been determined primarily by Raven (1980, 1985), Lau and Bisson (1980) and Brown et al. (1982a,b). The following fracture characteristics are derived from these reports.

The total Chalk River area studies by Raven (1980) was found to contain three fracture sets: fracture set A with a strike/dip maxima of 15°/80°W, mean spacing of 2.57 m and mean length of 3.53 m; fracture set B with a strike/dip maxima of 95°/85°S, mean spacing of 1.14 m and mean length of 2.94 m, and fracture set C with a strike/dip maxima of 155°/90°, mean spacing of 1.77 m and mean length of 2.80 m. For smaller sub-areas fractures were highly dispersed in orientation showing the presence of locally persistent fracture sets.

At the flow study site Raven (1985) indicates the existence of three major fracture sets at orientations of 105°/75°S,

235°/70°N and 150°/90°. The dominance of each of these sets varies spatially over the mapped area.

Borehole fracture surveys were conducted using a borehole television camera to determine fracture orientation frequency and aperture (Lau and Bisson, 1980). Fracture frequency logs for boreholes CR1, CR2, CR6 and CR7 indicate a range of about 1 to 12 fractures per meter with an estimated mean of about 3 fractures per meter. At the flow study site, Raven (1985) identified the following borehole sets in order of decreasing strength: 250°/70°N, 105°/65-75°S and 145°/90° subhorizontal.

In a general synthesis of the fracture data from Chalk River, Atikokan and URL, Brown et al. (1982a,b) made the following comments:

- fracture characteristics are consistent from scale to scale and are in accordance with the tectonic history of the area;
- fractures with dip of 40° demonstrate that the surface population is no different from the subsurface population.

Complete fracture data for Chalk River is given in Appendix C.11.

5.12 Whiteshell Research Area

5.12.1 Site Description

AECL's Research Area 3 (Figure 5.24) is located on the property of the Whiteshell Nuclear Research Establishment (WNRE) near

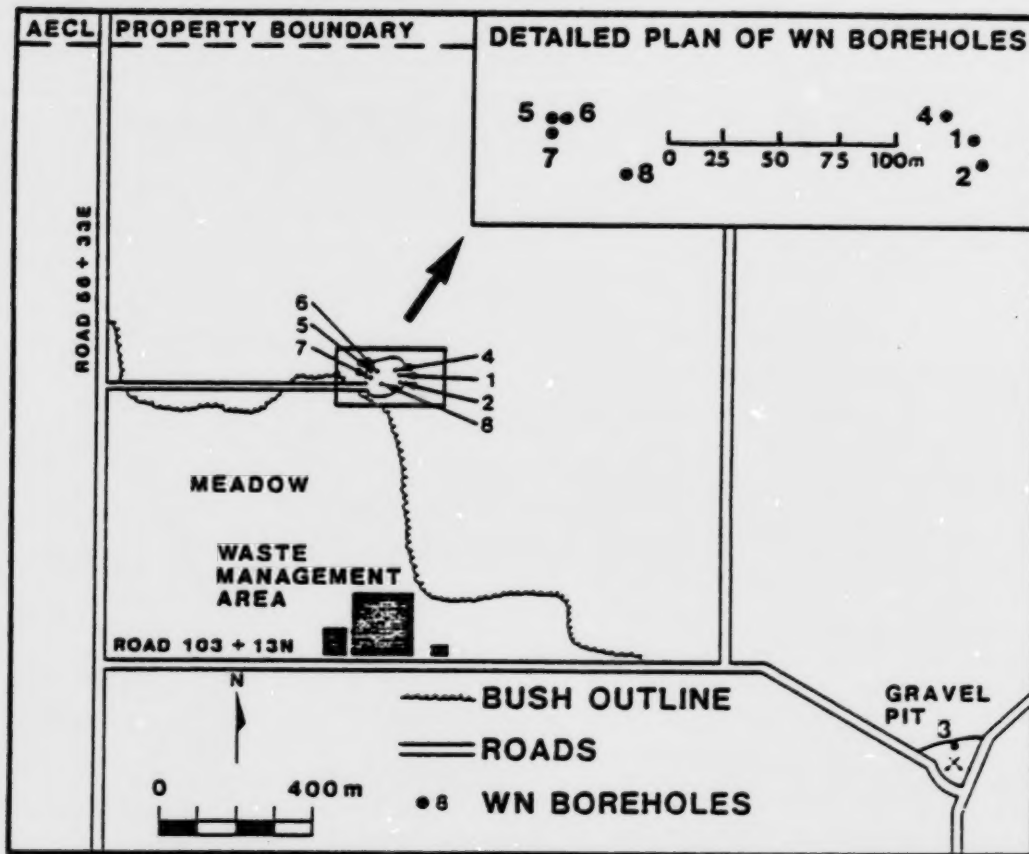


Figure 5.24 Location of the Whiteshell Research Area Boreholes (Tammemagi et al., 1980)

Pinawa, Manitoba. This site is found on the southern margin of the Lac du Bonnet Pluton southwest of the URL site.

Geologic studies of the bedrock were completed at a reconnaissance level using outcrops found to the north and east of the site by Tammemagi et al. (1980). Surface mapping was limited by the general lack of outcrop due to thick overburden cover. Borehole lithology was determined by Lau and Bisson (1980) using borehole television surveys and core logging techniques. Geophysical surveys included airborne magnetic gradiometer, magnetotelluric soundings, seismic reflection (Huang and Hunter, 1980), tube waves (Huang and Hunter, 1981) and a complete suite of standard logging techniques (Keys (1978)).

Hydrogeologic testing by Davison (1980) using single and straddle packer borehole hydraulic and cross hole interference testing identified the hydraulic conductivity and hydraulic head distribution in several deep boreholes. Bottomley and Graham (1980) studied the geochemistry of deep groundwaters.

Eight boreholes are found at the site. These consist of three deep boreholes (400 m, 475 m and 830 m), one geochemistry borehole and four bedrock piezometers.

5.12.2 Permeability

In-situ permeability measurements for granite and granodiorite in the range of 2×10^{-13} to 5×10^{-7} m/s, have been recorded by Davison (1980 and 1981) for hydraulic tests conducted in boreholes WN1, WN2 and WN4 at the Whiteshell Nuclear Research Establishment. High values of permeability were recorded for intervals spanning open fractures (as determined by core log, T.V. camera or acoustic televiewer)

while low values were found in intervals with no observable fractures. These results were obtained using transient pressure response tests (pulse or slug tests) and constant pressure fluid injection tests. Comparisons between the injection test and pulse test for the same intervals indicated that either technique yields essentially the same permeability (Davison, 1981).

A consistent relationship of permeability with depth was not observed in WN1 (total depth 447.6 m) and WN2 (total depth 146.1 m). High permeability zones up to 10^{-7} m/s were found at depth in each hole. In WN1 the high permeability zone coincides with a fracture zone and is located at about 400 m below surface.

Laboratory studies of rock permeabilities conducted on cores from boreholes WN1 and WN2 resulted in the following values (Cooley and Butters, 1979): WN1 - 6.7×10^{-13} to 3.3×10^{-11} m/s and WN2 - 5.8×10^{-13} to 7.9×10^{-12} m/s for ambient pressures; and WN1 - 3.8×10^{-12} to 1.4×10^{-11} m/s and WN2 - 8.7×10^{-13} to 1.2×10^{-11} m/s for in situ pressures. Permeability was found to decrease with increasing effective stress, increase with temperatures above 75°C and be independent of pressure pulse up to 16% of the pore fluid pressure (Cooley and Butters, 1979).

5.12.3 Porosity

Porosity values of cores taken from Whiteshell boreholes have been determined by Wadden (1979), Radwan (1979) and Drury (1981). Wadden (1979) measured a matrix porosity range of 0.0016 to 0.0043 cc/gm for samples ranging from 24 to 460 m depth. This immersion technique resulted in a precision of

+ 7% on repeated measurements on the same sample. Radwan (1979) confirmed these results with a range of 0.0027 to 0.0060 using the same technique. The trend of the data suggests that porosity does not appear to decrease with depth. Drury (1981) measured similar porosities in the range of 0.001 to 0.009 with the same general trend.

5.12.4 Fracture Properties

The general lack of outcrop in the immediate area of the Whiteshell Research area limits the availability of fracture characteristic data for this site. However, considerable data is available for the URL site which is in the same granitic pluton. Borehole fracture data are presented by Lau and Bisson (1980), Lau (1980) and Davison (1980, 1981). In borehole camera surveys the following fracture orientations were determined (Lau, 1980): subhorizontal and 147°/90° in borehole WN1; two major sets intersected by WN2 trending subhorizontal and 342°/87°ENE; and four sets oriented 48°/48°SE, 32°/81°ESE, 0°/21°E and 205°/12°WNW in WN3. Appendix C.12 contains borehole fracture logs for Whiteshell.

Other fracture characteristics are not presented.

5.13 Miscellaneous Research Programs

In addition to the main research areas identified previously there are a number of sites and research programs that bear mentioning, although due to the quantity of available data or the limited scope of the project they do not warrant a separate section. These include the following:

- PAGIS (Performance Assessment of Geological Isolation Systems) Sites at Auriat and Barfleur France
- AECL's Research Area 7 - East Bull Lake
- Geothermal research program at Rosemanowes Quarry by Camborne School of Mines
- Geothermal research program at Fenton Hill, New Mexico by Los Alamos National Laboratories
- Exploration program for a feasibility study for a pumped hydroelectric energy storage program (the Illinois Deep Hole Project)
- Miscellaneous national nuclear waste isolation programs including those of Switzerland, South Africa, India, and Norway
- Research being conducted by researchers associated with various academic institutions (e.g., Evans, 1983; Snow, 1979)
- Data collected by commercial and industrial corporations (e.g. hydroelectric, mining companies)

Only the most pertinent of these investigations, those that bear particular relevance to the Canadian program or present significant quantities of data (albeit on one aspect of groundwater flow through fractured rocks), have been included in this review.

● PAGIS SITES

The work being performed for PAGIS is a program launched by the Commission of the European Communities (CEC). A number of sites (both reference and variant), representative of different geological conditions, have been selected for study. One of the selected geologic rock types is granite with the reference and variant sites being selected in France. The reference site is located at Auriat, approximately 30 km north west of Limoges on the western border of the Massif Central, a granitic batholith. Minimum thickness of the granite is estimated at

1000 m. In 1980, two vertical boreholes were drilled at the site, one to a depth of 500 m, the other to 1000 m. The selected variant site is at Barfleur in a coastal granite formation. Little information has been published regarding the nature of the tests conducted at either of these sites but their similarity to Canadian program warrants their inclusion.

The French site (at Auriat) is very similar in geologic setting to many of the Canadian research areas. PAGIS (1984) reported bulk hydraulic conductivity values for the Auriat site of 1×10^{-12} m/s at depths between 500 and 1000 m to as high as 6×10^{-9} m/s in the first 50 m. Porosity values range from 0.5 to 2%.

● East Bull Lake

AECL's Research Area 7 is the East Bull Lake site which is found 35 km east of Elliot Lake and 25 km north of Massey in northern Ontario. This site was chosen for investigation because it contains a large (13 km by 4 km) exposed gabbroic rock body that is easily accessible.

The gabbroic pluton is located within a tectonically complex part of the Archean Superior Structural Province close to the Proterozoic, Southern Structural Province (Ermanovics et al., 1982). The pluton trends east-west, is shallow-dipping, and composed of a layered intrusion of basal anorthosite and upper gabbro. Archean gneissic granites, granodiorites and metavolcanic rock surround the pluton. Intrusions of Proterozoic dykes and sheets of gabbro are found in the map area. Detailed geologic descriptions are provided by McCrank et al. (1983).

Geophysical surveys including: gravity, aeromagnetic, very low frequency electromagnetic (VLF-EM) and electromagnetic, were used initially to determine the size and shape of the pluton. Ground surveys included magnetic gravity, VLF-EM and seismic conducted on grid areas. Geophysical surveys were described by Watson (1982) and Redford (1983).

The detailed study area was mapped for structural discontinuities and lineaments. Several major lineaments including the Folsom Lake Fault were identified and mapped. In general, the area has a low fracture density in the near surface. Four diamond core holes to depths of 850 m and fourteen air percussion holes to depths of 90 m were completed at inclined and vertical orientations. Boreholes were core logged and surveyed by acoustic televiewer for fracture location orientation and frequency. Deep permeable fracture zones were identified at 410, 475, 640 and 775 m depth borehole EBL-1 and 405 and 580 m depth in borehole EBL-2 (Raven et al., 1984).

AECL's East Bull Lake is a relatively new research area and therefore only limited results of testing are available in the literature. Raven et al. (1984) provided the only hydraulic conductivity values available for this area and much of what is reported below is taken from this study.

Hydrogeologic studies by Raven et al. (1984) included hydraulic testing, hydraulic head monitoring and groundwater sampling. A drill water tracer program was implemented to improve the integrity of the groundwater samples.

Hydraulic testing at East Bull Lake was conducted by straddle and single packer injection tests, transient pressure pulse tests and pump tests. In the deep boreholes EBL-1 and EBL-2

hydraulic conductivities (equivalent rock mass) range from 1.2×10^{-12} to 6.0×10^{-7} m/s for injection and pulse tests. Pump test results conducted in the shallow boreholes resulted in transmissivities in the range from 4.1×10^{-9} to 4.2×10^{-6} m²/s.

Fracture characteristics for AECL's East Bull Lake Research Area have been determined by Raven et al. (1984) and are limited to major structural trends. Air photo lineaments were generally in excess of one kilometre length. Three lineaments were identified as noteworthy: the Folsom Lake Fault and lineaments trending 050° and 130°. The 130° lineament is associated with a steeply north dipping, northwest striking mafic dyke. The 050° lineament is likely associated with a large fracture zone or fault. The Folsom Lake Fault trends northwest. In boreholes deep permeable fracture zones were identified in EBL-1 at 410, 475, 640 and 775 m depths and in EBL-2 at 405 and 580 m depths. More complete fracture data is found in Appendix C.13.

● Evans, University of Arizona

Another research oriented program that is worthy of mention, in spite of the limited amount of data available, is the unsaturated flow and transport through fractured rock study undertaken by D.D. Evans of the University of Arizona (1983). To date only the Phase I portion of the study has been completed. This has involved examining the state of the art with respect to characterizing unsaturated fractured rock settings. In particular, a number of different techniques have been used to characterize fractured rock samples from both the Santa Nino mine and a site near Kingmar, Arizona. The samples obtained from the Santo Nino mine were granodiorite whereas the remainder were welded tuff samples. This site has been included in this review because significantly more data will be available in the future.

Evans (1983) presented porosity measurements on samples of granodiorite from a mine in New Mexico. His measurements were performed using both a mercury infusion and grain size analyses technique and are reported in Appendix B.13.

● Hot Dry Rock, Camborne School of Mines

The geothermal energy project being conducted in the Rosemanowes Quarry in Cornwall, U.K. by the Camborne School of Mines is also worthy of mention. The Hot Dry Rock (HDR) site is located near the center of the Carnmenellis granite outcrop. This pluton was emplaced about 285 Ma ago and has since undergone a complex tectonic history, the most recent major tectonic activity being the Alpin orogeny of 70 Ma ago. The site includes two wells drilled to depths of about 2 km. RH12 is cased to a depth of 1.75 km with an additional 357 m of uncased length. RH11 is cased to a depth of 1.45 km and contains an additional 772 m length of uncased hole.

Findings (with respect to hydraulic conductivity trends) at the geothermal research program at the Camborne School of Mines have been summarized by Pine (1983). His observations indicated that the permeability of the Carnmenellis granite at depths of 1500-2000 m is of the order of 10^{-5} darcies (10^{-17} m^2) at low injection pressures (less than 0.7 MPa) and increased by a factor of 6 when injection pressures were raised to 5 MPa.

The major fracture characteristics of the Carnmenellis granite, the rock that comprises the site of the Camborne School of Mines geothermal research program, has been described by Pine and Batchelor (1984). In summary, it can be said that two subvertical fracture sets, striking 155° and 75° dominate the structure of the site with a less important set (striking 30°)

also being present. These fractures are spaced at 1 to 5 m at the ground surface and increase to 3 to 10 m at a depth of 800 m. Horizontal fractures are present throughout but typically are at a wider spacing than the subvertical fractures.

- Hot Dry Rock, Fenton Hill

Another geothermal research area has also been a source of useful data - that being the Hot Dry Rock program conducted by Los Alamos National Laboratories at Fenton Hill, New Mexico. Little information describing either the geology of the site or its facilities is available. It is known that the major rock type at the site is granite which extends to a depth of 2900 m. This evidence was obtained through the drilling of two boreholes GT2 and EE2 at the site. Potter (1978) proposed a number of equations to describe permeability and porosity as a function of depth for this site.

The majority of the hydraulic test data pertaining to Los Alamos geothermal program (the HDR program at Fenton Hill, New Mexico) was determined by Potter (1978). Potter (1978) performed a number of laboratory measurements on cores for the purpose of examining the relationship between permeability and pressure and temperature. Potters findings are discussed in more detail in Section 2.2 while the results of his measurements are presented in Appendix A.13.

- Illinois Deep Hole Project

Another similar type of research project (Illinois Deep Hole Project) was conducted in northern Illinois by several researchers for Commonwealth Edison of Chicago. This project was essentially an exploration program for a pumped

hydroelectric energy storage project. Three continuously cored holes were drilled into the Precambrian granite through approximately 670 m of Cambrian and Ordovician sandstones and carbonates (Haimson and Doe, 1983). Detailed stress and permeability measurements were conducted in only UPH-3. The other two holes were backfilled in accordance with state regulations. This project is of interest because it presents one of the few documented cases where in-situ stress and permeability measurements have been made simultaneously.

Permeability measurements for the Illinois Deep Hole Project are summarized by Haimson and Doe (1983). They indicated that permeability at the site displayed an overall reduction with depth from about 10^{-4} darcy (10^{-16} m²) at 700 m to 10^{-8} to 10^{-9} darcy (10^{-20} to 10^{-21} m²) at 1600 m. They do note however that permeability is highest in the zones of greatest fracturing. No conclusions were made regarding the state of stress in the borehole and its possible impact on permeability measurements.

The fracture system at the site of the Illinois deep hole project was characterised primarily through core logging although a number of geophysical logs were also employed. Haimson and Doe (1983) summarize the system as follows. Forty seven logged fractures were oriented enabling three moderately well-defined sets N55°E - 10°, N40°W - 15° and N90°E - 10° to be identified. Fracture density values for UPH 3 indicate two zones of fractures, one located near the top of the granite (700-950 m) and the other at a depth of 1150-1320 m.

● NAGRA Program

Nationale Genossenschaft für die Lagerung Radioaktiver Abfälle (NAGRA) was established by producers of radioactive waste in Switzerland to develop the required technology and establish a safe method for the storage and disposal of these hazardous wastes. The Swiss program considers the most suitable disposal environment to be the crystalline basement underlying the northern part of Switzerland. Twelve deep borehole are to be located in an area bounded by Olten in the west, Zurich in the east and the Rhine River to the north, to investigate the rock mass. To date, about half of the boreholes have been completed. Unfortunately only limited data on the first borehole (Boettstein - total depth approximately 1500 m) are publicly available and much of the information is yet to be released.

Results of permeability measurements from the Swiss NAGRA program indicated a range of hydraulic conductivity of 10^{-13} to 10^{-6} m/s for the granite basement rocks of northern Switzerland. These results were obtained using single and double packer equipment and slug, pulse and drill stem test techniques on the Boettstein borehole. In general, the hydraulic conductivity decreases from the surface to a depth of about 800 m. Below this depth and to the bottom of the borehole (1500 m) the hydraulic conductivity varies without a consistent trend between 10^{-13} and 10^{-10} m/s.

Long term monitoring of the Boettstein borehole using a multiple packer casing installation resulted in hydraulic conductivity measurements for specific long intervals. These results, which are likely indicative of large volume, bulk rock hydraulic conductivities ranged from 10^{-14} to 10^{-11} m/s and show a general decrease with depth.

● Miscellaneous

One of the most significant (from the standpoint of magnitude of observations) studies that was reviewed is the data presented by Snow (1979). He presented a summary of computed permeabilities for 5862 packer injection tests conducted in 12 different sites. The hydraulic conductivity summary from this report has been included in Appendix A.13.

Several researchers have investigated and/or reviewed porosity measurements independently of the major research programs identified earlier. Most notable of these are Norton and Knapp (1977) and Evans (1983).

Norton and Knapp (1977) of the University of Arizona determined bulk (total) porosities on approximately 70 different samples of crystalline rocks as part of a National Science Foundation research grant. They concluded the the porosity of hydrothermally altered calc-silicate and plutonic rocks was significantly higher than for their unaltered equivalents. Isotropic metamorphic rocks were found to have a total porosity ranging from 3×10^{-2} to less than 10^{-2} while anisotropic rocks exhibited a wider range from to less than 10^{-2} to 10^{-1} . The complete set of porosity values as determined by Norton and Knapp (1977) are presented in Appendix B.13.

A number of ongoing research programs were known to exist at the time of this review; however, data from many of these sites were not available. Every reasonable attempt was made to obtain information on these sites but in spite of these attempts, documentation on several research areas is incomplete and in some cases only acknowledgements of the existence of these sites can be made. These include data from sites in South Africa, Norway and India, as well as the Wairakci Geothermal Field in Japan and the Fanay-Augères site in France.

6.0 SUMMARY AND CONCLUSIONS

This report has compiled information on the distribution and properties of fractures and other hydrogeological parameters such as permeability and porosity for crystalline rock. The study has compiled and reviewed values of these parameters as reported from world wide investigations and has included much of this data in tabular form in the appendices. Both the parameters, as well as the conditions under which they were measured, are presented, when available. Relationships between the measured parameters and other variables have been included whether observed in the data or reported in the literature. The vast majority of information available in the literature pertains to relatively few sites, mainly research areas for nuclear waste disposal programs or geothermal investigations. This has not however by any means precluded the inclusion of data from other sources, such as that arising from university research, conferences, symposiums or journal publications. Other sites have been included where geologic and hydrogeologic data are presented with detailed fracture information. Information from private sector companies has also been reviewed where available.

Permeability/hydraulic conductivity data were found to be extensively reported in the literature. However, difficulties arise when comparing the measurements performed at different sites. These difficulties are due to both inconsistencies in the approaches employed as well as the incomplete nature of many the studies reviewed. For example, most researchers will tend to report hydraulic conductivity values of a particular region of interest but neglect to supply adequate information (regarding fluid properties) to obtain an actual permeability value. Furthermore, many of the reports reviewed give incomplete documentation on test configuration (e.g., test

interval, scale, etc.) or analytical technique. In spite of these difficulties, the following can be said regarding the permeability of fractured rock systems. Permeability tends to be dominated by the existence of fractures, although the existence of a variety of factors (e.g., infilling, stress) complicates the relationship between the two quantities. The majority of hydraulic conductivity values reported range from 10^{-3} m/s to 10^{-13} m/s with the higher values pertaining to highly fractured rock with the lower values describing intact rock (matrix) values. Permeability may vary with depth, however, the dominance of permeability profiles by the above mentioned fracture zones tends to mask this characteristic. These fracture zones also tend to mask any relationship that may exist between permeabilities and specific rock types. The rock dependent portion of hydraulic conductivity (i.e., permeability) has been shown by several researchers to be a function of temperature and stress. However, the exact nature of this relationship (due to the interaction of various mechanisms) is difficult to predict a priori.

Porosity is another parameter which was examined in this review because of its relative dominance in the equation describing the storativity of the medium. Other components of this variable (e.g. fluid and rock compressibility) are either limited in the magnitude of their variation (e.g. fluid compressibility) or the magnitude of their contribution to the overall component (e.g., rock compressibility) is small. Porosity is also useful from the standpoint of calculating the movement of solute through a fractured rock system through the calculation of an interstitial velocity. Porosity may be classified a number of ways, with total (bulk) porosity being comprised of a matrix and fracture porosity. Other classifications of porosities include effective (or interconnected) with the term residual or dead end referring to the non-interconnected pore space. Matrix porosities tend

to comprise the majority of the total or bulk porosity. For most crystalline rocks considered in this review this value ranged from 0.1% to 1.0% although several researchers report values outside this range. Fracture porosities can be determined by aperture measurements or tracer tests (in which case they are effective) and usually tend to be of the order of 10^{-4} .

Fractures in plutonic rocks, their properties, mode of origin, methods of measurement and presentation of data have been described as reported in the literature. Fracture characteristics, where described with geological and hydrogeological information, have been presented for a number of research sites around the world. Fractures within plutonic rock environments have been shown to be highly variable and dependent on the geologic setting and tectonic history. Position within the pluton and proximity to major structural features also contribute to the dispersion of the fracture characteristics. Correlations between surface and subsurface data are hindered by data collection techniques and the ability to collect representative samples of the fracture system using surface/borehole mapping.

The conclusions derived from this review regarding the characteristics of fractures in plutonic rocks are limited because of the variability and uncertainty with regards to fracture systems. In general, fracture systems are not randomly oriented but occur in numerous, similarly oriented sets. With some limitations the present mapping techniques are suitable for describing the fracture systems provided sufficient, corrected data are used and statistical analyses are used in the interpretations (to ensure the representativeness of samples). The sets for subvertical to vertical fractures can be identified from the surface to the subsurface

but extrapolation to depths greater than 100's of meters requires detailed three-dimensional mapping. Horizontal and subhorizontal fractures cannot be correlated to depth due possibly to the lack of occurrence or the limitations of the sampling techniques. Scales of measurement for fracture characteristics are generally comparable, however, the variability of fractures with position and structural setting in the pluton restrict small scale measurements in comparison to large (regional) scales.

The review of the data compiled as part of this study has been qualitative (and subjective) in nature. To more accurately determine what, if any, trends may exist in the data it is recommended that a rigorous statistical analysis be conducted. Such an analysis, although very useful in examining correlations in the data, was beyond the scope of the present study.

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